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TECHNICAL REPORT RF-75-2

ROOT CAUSE ANALYSIS – A DIAGNOSTIC FAILURE ANALYSIS TECHNIQUE FOR MANAGERS

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26 MARCH 1975

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Redstone Arsenal, Alabama

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14

1. REPORT NUMBER: RF-75-2
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:

6

4. TITLE (and Subtitle): ROOT CAUSE ANALYSIS – A DIAGNOSTIC FAILURE ANALYSIS TECHNIQUE FOR MANAGERS,

9

5. TYPE OF REPORT & PERIOD COVERED: Technical Rep[redacted],
6. PERFORMING ORG. REPORT NUMBER: RF-75-2

10

7. AUTHOR(s): A. E. Magistro [redacted] L. R. Seggel
Augustine Lawrence

8. CONTRACT OR GRANT NUMBER(s):

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Commander
US Army Missile Command
ATTN: AMSMI-RF
Redstone Arsenal, Alabama 35809

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:

11. CONTROLLING OFFICE NAME AND ADDRESS:

12 99p.

11

12. REPORT DATE: 26 Mar[redacted]75
13. NUMBER OF PAGES: 95

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

None

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Root cause analysis
Failure analysis

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents a proven technique for technical problem analysis. An analysis method is described and a format presented which is aimed at the systematic solution of failures. Examples of typical problems and solutions are included in addition to guidance, for the organization and operation of teams charged with establishing the "root cause" of failures. Comments on group processes should be helpful to new root cause team managers in the operation of the teams, and a bibliography of material on problem solving and decision making provides sources of data related to the topics. (Continued)

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ABSTRACT Concluded (Block 20)

Although the text focuses on hardware development activities, it can readily be seen that the root cause analysis technique has broad application to general problems, e.g., low sales, business reversals, increased costs, etc.

This technique is easy to learn and requires no special skills. Use of the format provides explicit data for the systematic evaluation of postulated failure modes. Rigid adherence to this technique makes the root cause of the problem obvious through the process of elimination and, therefore, assures that the source (root) of the problem, not the symptoms, is dealt with.

PREFACE

The root cause analysis technique was devised in 1967 and refined by the LANCE Project Office, Redstone Arsenal, Alabama, during the LANCE development. It has been rigorously applied to all LANCE system technical problems and, in addition, it was applied to certain failure analysis activities conducted by the staff of the LANCE System Engineering Manager, Picatinny Arsenal, Dover, New Jersey. The method resulted from the cooperative efforts of the LANCE project technical staff, LTV Aerospace Corporation — Michigan Division, Picatinny Arsenal, and numerous participants from several Government and institutional agencies. Applications were diverse and included in-flight missile failures and severe production problems on components of missile systems. Neither schedule slippage nor cost overrun was encountered when the root cause diagnostic failure modes analysis technique was relentlessly applied on the LANCE project during the period 1969 through 1975.

Augustine E. Magistro has participated in root cause analysis task teams in a number of capacities including team member and Blue Ribbon Panel reviewer, team leader, and consultant. He has applied his skill and failure analysis in electronic fuzing systems, solid-state timers, and thermal battery production problems. He is a 1952 graduate of Lehigh University with a BS degree in mechanical engineering.

Lawrence R. Seggel graduated from Lafayette College in 1957 with a BS degree in industrial engineering. Since 1963 he has been involved in the systems engineering activities within the LANCE Project Office. In 1968 he became the Chief, Technical Management Division. This report is based largely on his experience.

Special acknowledgment is given to John A. Robins, Deputy LANCE Project Manager, whose managerial drive and insistence upon "finding a way to be sure we are correcting the right problem" produced the atmosphere in which this technique was devised and perfected.

During the LANCE activity, it became evident that in many engineering programs "our greatest skill is not in never failing but in rising each time we fail." It is hoped that the material presented in this report will encourage and support those individuals who encounter technological failures by helping them respond in a systematic and planned manner.

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1. Introduction

Throughout the development of the LANCE Missile System, or any technical development activity, hardware failures occur. In some cases the failure is catastrophic, such as an explosion or crash, and in others the failure is subtle, i.e., in the form of an out-of-specification value of performance of some component or subsystem. In this report, any performance beyond three standard deviations of nominal is termed a failure. A primary task of management and systems engineers is to establish the normal performance limits for the hardware, recognize abnormal performance (failure) when it takes place, determine the cause of failure, and derive effective solutions.

The determination of the cause of failure is often the most formidable task presented to engineers during a development. Failures are often the result of the unexpected and the intense pressure to meet schedule and cost goals. In addition, the desire to quickly solve the problem and show "how intelligent we are" becomes almost uncontrollable.

During the early phases of the LANCE project, the Government agencies and contractors involved were very effective at quickly applying "fixes" to failures. In many cases, the apparent problem was treated and several apparent problem symptoms were also treated, but often the same failure recurred. In the early part of the program, corrective actions were applied several times to treat the same symptoms. Significant costs in dollars, time, and anxiety were suffered by several levels of management each time the corrective action was inadequate.

It became evident that a technique which assured that the root cause of a failure was detected and removed was essential. System development cancellation was a real threat, and in this atmosphere a series of innovations evolved which produced the root cause analysis technique.

The root cause analysis technique produced dramatic and effective results. The basic root cause for each failure was clearly established, and in the majority of the cases it was reproduced in the laboratory. Demonstration of a complete understanding of the failure mechanism preceded any attempts at engineering solutions. Solutions to known specific problems, whose phenomena are clearly understood, are generally straightforward and need to be applied only once with complete confidence that the problem will not have to be encountered again.

This technique is a special presentation of the scientific method and it is believed that root cause analysis is of general benefit in solving a variety of problems. Experience with other Army development activities and several contractor organizations shows that they had experienced, or were experiencing, similar difficulties in problem solving. Those that have applied the root cause technique have become advocates of its merits.

This report presents a description of the root cause analysis technique and explores many of the related factors and approaches to teamwork in problem solving activities.

2. Technique of Root Cause Analysis

The technique of root cause analysis has proven to be the most significant engineering management tool employed by the LANCE missile system development team. The technique involves a thorough, organized, and rigorous analysis of each hardware failure, or apparent failure, to firmly establish the one root cause. To support the analysis and to assure an explicit understanding of the root cause of failure, each failure is duplicated. The next step after establishing the mechanism of failure is to apply solutions and corrective actions.

The problem begins with the occurrence of an apparent hardware failure. With a brief description of the problem, a root cause manager is designated to organize a team of engineers with expertise in a broad range of fields to perform the first of many critical steps in the analysis.

All available data should be gathered for review and cataloged in terms of its validity, i.e., personal observations which are or are not collaborated, instrumentation data, recovered hardware, etc. To provide a "statement of the problem," the initial task is to specify the problem in terms of what happened and the sequence of events leading to the problem.

Furnished with the essential knowledge of the item under investigation, a group (not more than five persons) lists every conceivable cause for failure. This technique utilizes brainstorming to produce a list of postulated modes of failure. In general, brainstorming employs the deferring of judgment as a means for obtaining a large number of possibilities or alternatives, i.e., discussion and ideas are freely evolved and recorded without evaluation of the idea at the time of its expression. Thus, the procedure permits a large quantity of possibilities to be recorded in a short period of time, and the broadest view of the problem is obtained before a conclusion is reached. The separation of the production of failure possibilities from their evaluation provides a greater opportunity for detecting subtle causes and reduces shortsightedness in examining failure modes which may be remote but possible. Even the most remote possibilities should be listed since there are no real data constraints or boundary conditions. From this list (which may be added to at any time but never subtracted from) the root cause of the failure will be determined.

At this point, the formal diagnostic team is established to conduct the analysis to completion. Considerations for team composition, leadership, motivation, and other valuable problem solving considerations are presented in subsequent sections so they may be thought of in context with the objective of the root cause analysis technique.

The format of the root cause analysis chart (Figure 1) is a simple one; however, it must be conscientiously completed and updated to be effective in keeping the progress and, ultimately, the results of the analysis before the team. The column headings of the chart are as follows:

a) Failure mode - All potential failure modes from the initial postulated list are entered, one to a page, and added to as additional modes are evolved.

b) Failure sequence - The mechanism of the postulated failure mode is briefly described for each failure mode entered.

c) Supporting data - Actual test data "facts" and substantiated analyses that are established from detailed investigation of the failure mode are listed. All facts that support the mode are listed in enough detail to be understood by the team.

d) Refuting data - All facts established during the detailed analysis of all data that refute the postulated failure mode are entered.

Note: It is essential that only established facts be entered in the supporting and refuting data columns. There is no allowance for supposition beyond the failure mode and failure sequence columns because the weight of the facts established and listed in the supporting and refuting data columns will determine which failure modes are not the cause, which are potential contributors to the failure, and which one is the most probable root cause.

e) Additional data and tests required - As the investigation proceeds it will become clear that there are gaps in the analysis or data available which, if filled in, would produce a basis for a firm conclusion relative to likelihood of the postulated failure mode being the cause of the observed failure. The definition of those investigations, whether analysis or tests, that will fill the data gaps are entered in this column. The estimated completion of those additional investigations are also entered so that the team objectives are understood and timely input is maintained. The charts are "living" documents and when additional data are made available, prior entries are deleted (lined through) and the results entered in either the supporting or refuting data columns.

FAILURE INDICATION: CAUSE PROBABILITY ESTIMATE:

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADDITIONAL DATA TESTS REQUIRED

CORRECTIVE ACTION: (CHECK ONE) NONE REQUIRED

CONCLUSION:

Figure 1. Root cause analysis chart.

There is a space on the chart where a simplified statement of the observed failure indication may be entered. Other entries that may be used for summary notations are also provided. The final determination of the failure mode cause probability estimate should be stated in terms of "not cause," "probable contributor," "unlikely cause," "likely cause," and "root cause." An indication as to whether corrective action is required should be entered together with any conclusive statements considered desirable.

Figure 2 is a root cause analysis chart with instructions for making entries where appropriate. Since the instructional entries are included, this root cause analysis chart instruction format can be provided as a "handout" to root cause team members to help them understand the intent of the root cause analysis chart.

Figure 3 is a root cause worksheet. Since the root cause analysis chart is cramped for space, thereby requiring effective summarization of key points, a worksheet has proved helpful to the individual investigators for whom summarization is not easy. By providing more space for supporting and refuting data, the investigator can write a complete thought for the use of other members of the team. Summarization of those thoughts for entry into the root cause analysis chart can be accomplished later by the subteam or team leader.

An example of a final summary report resulting from an actual investigation is presented in Appendix A.

The root cause analysis chart format fulfills several significant purposes:

a) Provides a prompt overview of the status of any point during the failure analysis process. This is valuable to the team and to management.

b) Describes and plans follow-on activity required to complete the analysis.

c) Provides an auditable review record in the simplest terms which allows independent assessment by disinterested parties such as "red teams" and "blue ribbon panels."

d) Concisely presents the balance between confirming and refuting data upon which determinations are based.

e) When the root cause is identified, the information on the format explicitly describes the failure process and demonstrates that other causes are eliminated from contention.

FAILURE INDICATION: ENTER BRIEF STATEMENT OF FAILURE INDICATION

CAUSE PROBABILITY ESTIMATE: USED DURING EARLY STAGES TO INDICATE CAUSE PROBABILITY WHEN LITTLE IS KNOWN ABOUT THE FAILURE

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADDITIONAL DATA TESTS REQUIRED
LIST ALL POSSIBLE MODES OF FAILURE. MODE IS DEFINED AS THE BASIC CAUSE OF THE OBSERVED FAILURE. FAILURE IS DEFINED AS THE INABILITY OF A SYSTEM, SUBSYSTEM, COMPONENT, OR PART TO PERFORM ITS REQUIRED FUNCTION. THE DESCRIPTIONS CHOSEN SHOULD BE SPECIFIC AS IN THE EXAMPLES. LIST ONLY ONE MODE PER PAGE. EXAMPLES: ITEM SHORT, ITEM OPEN, IMPEDANCE, FIN FAILURE, (SEE APPENDIX A).	LIST ALL CONCEIVABLE MECHANISMS WHICH COULD CAUSE THE FAILURE MODE TO OCCUR. THERE MAY BE SEVERAL MECHANISMS THAT COULD CAUSE A GIVEN FAILURE MODE TO OCCUR.	ENTER ALL DATA WHICH SUPPORT THE POSTULATED MODE AND SEQUENCES. EACH ENTRY SHOULD BE NUMBERED TO AGREE WITH THE FAILURE SEQUENCE ENTRY IT SUPPORTS.	ENTER ALL DATA WHICH REFUTE THE POSTULATED MODE AND SEQUENCES. EACH ENTRY SHOULD BE NUMBERED TO AGREE WITH THE FAILURE SEQUENCE ENTRY IT SUPPORTS. (THERE MAY BE SUPPORTING AND REFUTING ENTRIES FOR EACH MODE AND SEQUENCE.)	AS A RESULT OF ENTRIES IN ANY OF THE COLUMNS ENTER SPECIFIC DESCRIPTION OF WHAT FACTS OR DATA MUST BE COLLECTED TO COMPLETE THE PROBLEM SOLVING PROCESS.

CORRECTIVE ACTION: (CHECK ONE)

NONE

REQUIRED – LIST THE STEPS OR MEASURES THAT CAN BE TAKEN TO PREVENT A FAILURE IN THIS MODE, e.g., DESIGN CHANGE, ADDITIONAL QUALITY CONTROL, TEST OPERATIONS, ETC.

CONCLUSION: ENTER FINAL ESTIMATE OF THE CAUSE PROBABILITY AND SUMMARY STATEMENTS BASED ON THE CONTENT OF EACH MODE ANALYSIS.

Figure 2. Root cause analysis chart instruction format.

<table>
<tr><td colspan="2">FAILURE INDICATION:</td><td colspan="2">FAILURE MODE AND SEQUENCE:</td><td colspan="2">ADDITIONAL DATA TESTS REQUIRED:</td></tr>
<tr><td colspan="3">SUPPORTING DATA</td><td colspan="3">REFUTING DATA</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="6">CAUSE PROBABILITY ESTIMATE:</td></tr>
<tr><td colspan="6">CONCLUSION:</td></tr>
</table>

Figure 3. Root cause worksheet.

This technique requires discipline to produce solutions. It takes patience and discipline at all levels of management to allow the analysis team to do the thorough diagnostic job that is required. Understanding can not be legislated, it has to be worked for. To a mature management this is the only course that assures success. The saying "do it right the first time and you will not have to do it again" continues to hold true.

The tool has been described; the techniques for its use and realizing its full utility now need to be discussed.

3. Root Cause Organization

How do you "get into" a root cause analysis? This section presents a discussion of the typical root cause analysis organizations, flow diagrams, red teams, and blue ribbon panels. The ability to identify what problems require what magnitude of effort is obtained through experience; however, some ideas to assist in this area will be presented in this section.

Figure 4 presents a typical block diagram of an ad hoc root cause analysis organization. The ad hoc team approach is shown because it represents an organization appropriate for the investigation of the most difficult types of failures, i.e., those where the data base is small, the known facts are few, the areas of possibility are many, and the time to reach a total understanding is expected to be more than 2 months. After the initial failure modes are listed on the root cause analysis chart and the initial failure data are reviewed, it is generally apparent what type and magnitude of organization is necessary. Simplifications of this basic organization are obvious.

When a problem is of such magnitude as to require long term involvement of personnel from several major organizations, it may prove beneficial to have an understanding at the highest levels of those organizations so that the support required and provided will be the type and quality needed and will be continuous. In the Government, separate commands and agencies as well as contractors and institutional consultants may be involved. Similar situations arise within industrial concerns. A charter of operations prepared by the primary organization and signed by the heads of the supporting organizations and the root cause team leader can prepare an effective and efficient analysis.

Factors to be presented in a charter of operations are:

a) A brief statement of the problem

b) A statement of the significance of the problem

c) Designation of the root cause team leader

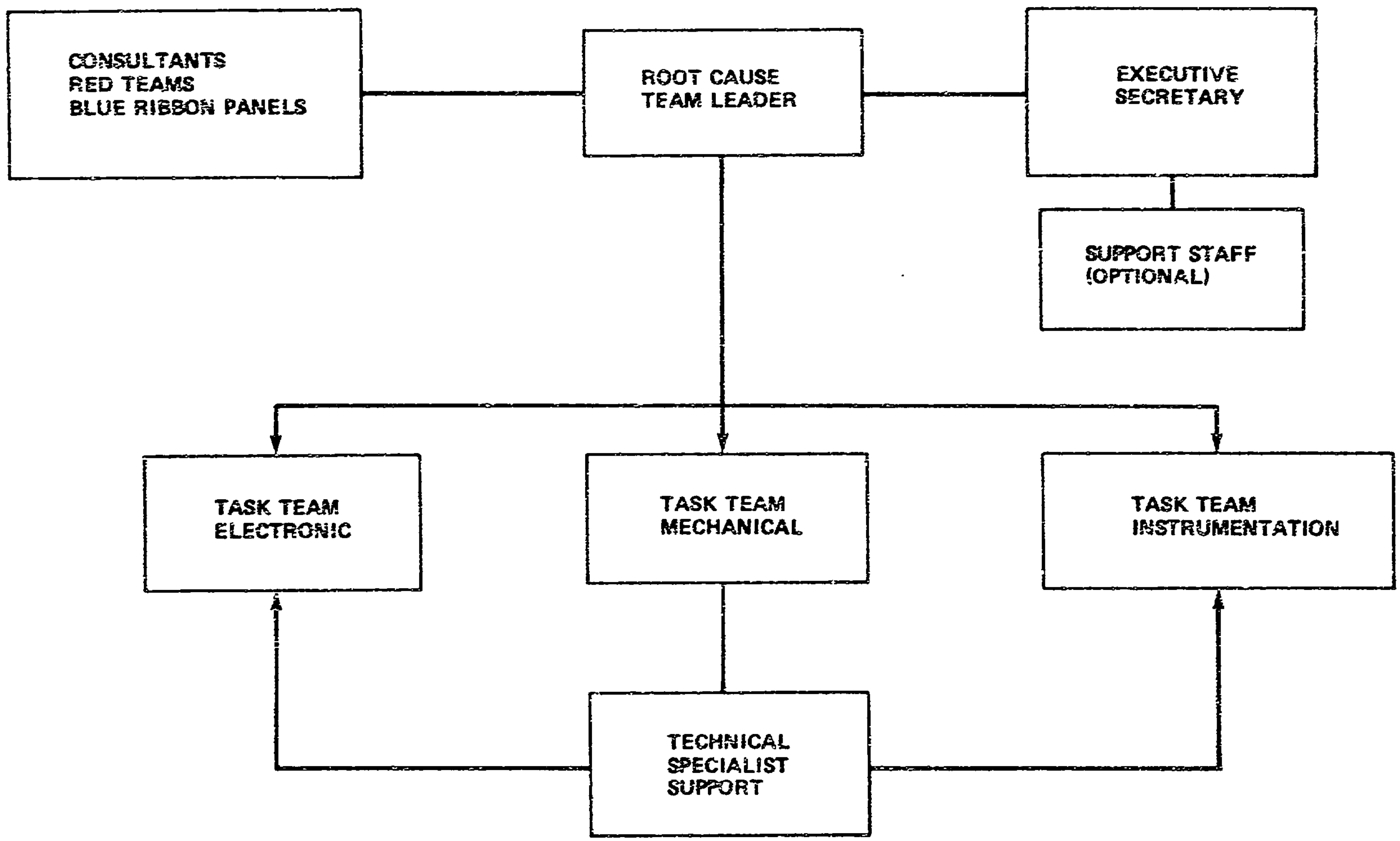

Figure 4. Typical block diagram of ad hoc root cause organization.

d) Designation of the site for the team's operations

e) Definition of the support required of each supporting organization; names of specific individuals, if practicable

f) Best estimate of the duration of the investigation.

The root cause team leader is obviously the hub of the analysis. The team leader does not need to be a technical expert, but should possess most of the good characteristics of a top manager (i.e., an organized and disciplined individual). The capacity to understand and appreciate the abilities and idiosyncracies of the members of the team in order to obtain their best efforts should also be qualities of a team leader. He should possess the ability to anticipate personality conflicts, resolve them, and create a cohesive team. The team leader should have the drive to keep the analysis on course with as high a rate of progress as possible. Finally, he should have the capacity to recognize the answer when he sees it. Some of the techniques used by team leaders are discussed in subsequent sections.

The root cause team leader will perform the following functions:

a) Direct and control the activities of the team

b) Prepare the ad hoc team charter if required

c) Arrange for the team staffing

d) Describe the root cause analysis technique using this reference of a typical example for the problem under study

e) Establish task teams

f) Distribute root cause analysis charts to task teams

g) Assure that assignment due dates are met

h) Prepare cost estimates and authorizations for management as required

i) Arrange for technical specialist support as necessary

j) Arrange for red team or blue ribbon panel reviews if the problem warrants that magnitude of independent review.

Each team should have an executive secretary whose duties should include the following:

a) Prepare listing of participants with addresses and phone numbers

b) Arrange meetings

c) Assure preparation of minutes of meetings

d) Distribute minutes, reports, and data to the team members

e) Prepare and update the root cause analysis chart and report

f) Maintain a chronological file of all material to serve as a reference information bank and allow the various task teams to acquire data without slowing up other teams. This can be very important because the regular cross-feeding of information among the task teams speeds up the analysis process.

g) Summarize the findings of the various task teams and issue interim data to the teams

h) Prepare visual aids of briefings, conferences, etc.

i) Direct the preparation of the final report of root cause.

The executive secretary will require secretarial support as a minimum and additional support will be dependent upon the magnitude of the problem under study and the size of the group. The organization and supporting staff should be kept to the minimum because larger groups are unwieldy and costly. There is no substitute for good judgment in this area.

The task teams may consist of one to not more than five individuals, with a given area of expertise. It will be the task of the team to evaluate the available data and develop supporting and refuting data for the root cause analysis chart on those failure modes that are within their area of expertise. The task teams will also determine what additional data are required to resolve each failure mode. They should arrange or perform the necessary analyses or tests to be conducted and write individual fact sheet reports on their findings. Dissemination of information/findings among task teams and to the root cause team leader on a timely basis cannot be overemphasized. The crossfeeding of information allows for maximum progress and minimizes duplicative effort. Initial internal independent reviews can often be provided by other task teams and the team leader and serve as an initial critique of the validity of the findings and conclusions drawn. In this way, perspective is gained. We all have the tendency to get our nose into the grass so we cannot see the lawn when we get immersed in a problem investigation.

The task teams may add to the failure modes list as the investigation provides new insights. Failure modes, once stated, cannot be arbitrarily deleted.

Technical specialist support of the activities may be necessary to perform specific analyses or tests. This support should be provided, when necessary, to assure that the task teams' time and talents are effectively used. Additionally, a given analysis may require skills not present on the task team itself. Such help should come from the specialist support capability (Appendix B lists some sources of technical skills).

Task team leaders should perform the following functions in conjunction with team members:

a) Present established facts describing the problem

b) Assist in listing "failure modes"

c) Complete "failure sequence" on root cause analysis charts

d) Fill in "supporting data" and "refuting data" columns on root cause analysis charts

e) Develop follow-on activities test and analysis requirements with due dates

f) Obtain support of technical specialists as necessary

g) Provide data outputs and findings to root cause team leader and other task teams

h) Iteratively update root cause analysis charts and assist in assigning cause probability estimates for each failure mode.

Consultants, red teams (who critique by playing the devil's advocate), and blue ribbon panels (who bring widely recognized expertise to the analysis critique) are an important adjunct to the diagnostic efforts and their broad use in these investigations generally falls within two areas. First, blue ribbon panels and consultants may bring expertise in an area that is not available within the organization and may be employed directly on task teams, as in the role generally applied to technical consultants. The second area is an important one and concerns maintaining perspective and review of findings. Red teams and blue ribbon panels can provide objectivity and sound advice on future courses of action, on a periodic basis (not more than monthly), as the investigation progresses. In addition, they play the role of the devil's advocate when the investigation is completed. In this way they can help assure that all relevant areas are being investigated and the logic of the findings and conclusions are unassailable. Sometimes it is of benefit to have "disinterested parties" review your work, if for no other reason than to make you organize and examine your logic. As a result, the simple preparation for a red team or blue ribbon panel review may be considered a major quality assurance tool. The objectivity brought to an analysis by these auditing groups should not be overlooked on the more difficult problems. One of the greatest technical abilities is the ability to recognize when we do not have the knowledge to handle a problem and, therefore, need help.

A red team or blue ribbon panel should perform the following functions in support of a root cause analysis:

a) Independently critique the facts and approach taken by the team at periodic intervals — after the root cause is determined

b) Review the root cause findings

c) Provide guidance on possible approaches not accounted for by the team

d) Issue a written report of the findings (which may be appended to the root cause final report).

From the root cause analysis flow diagram shown in Figure 5, it is clear that the ultimate definition of the root cause may occasionally occur after a cursory review; however, the bulk of the problems encountered will require the disciplined iterative process.

The initial data from a failure may indicate the nature of the failure or limit the areas of concern. In the later stages of a development activity, when the data base is very broad, most failures tend to fall into this category. There should be no doubt, however, that the approch to the root cause analysis must be rigorous, critical, and disciplined for problems with a broad data base as well as those with meager data bases. The difference in the level of problem is shown only in the fact that the root cause may be determined in a week to a month by a team consisting of a few members. The disciplined approach must be adhered to for these short term problems.

Figure 6 is a graphic representation of the root cause analysis cycle from observation of the failure through corrective action, implementation, and follow-up. Typically, variations of this cycle of activity with its numerous inputs and outputs will result in a specific failure analysis activity.

Solutions should not be developed until the root cause is known. The exigencies of each situation might dictate that solution development be conducted parallel with the root cause analysis. Naturally, this increases the cost exposure if the solution is for the wrong problem. Be careful, do not implement solutions until you have the root cause.

4. Importance of Verifying Facts

There is unlimited involvement when dealing with unverified facts. Unfortunately, you will go far astray pursuing phenomena that might not have existed — what a colossal waste of energy. As indicated in Section 2, the first major activity when problem solving is to arrive at a valid statement of the problem.

Recognizing that a problem exists is necessary to begin fact verification. That perception may result from failure of developmental hardware to perform as expected, declining sales, a market fail to develop, or many other "failures." To have made the determination that a problem exists, the manager must have a set of data which he believes to represent facts. Thus, the first step in understanding the root cause of a problem (verification of the initial facts) is reached. Can the manager believe them?

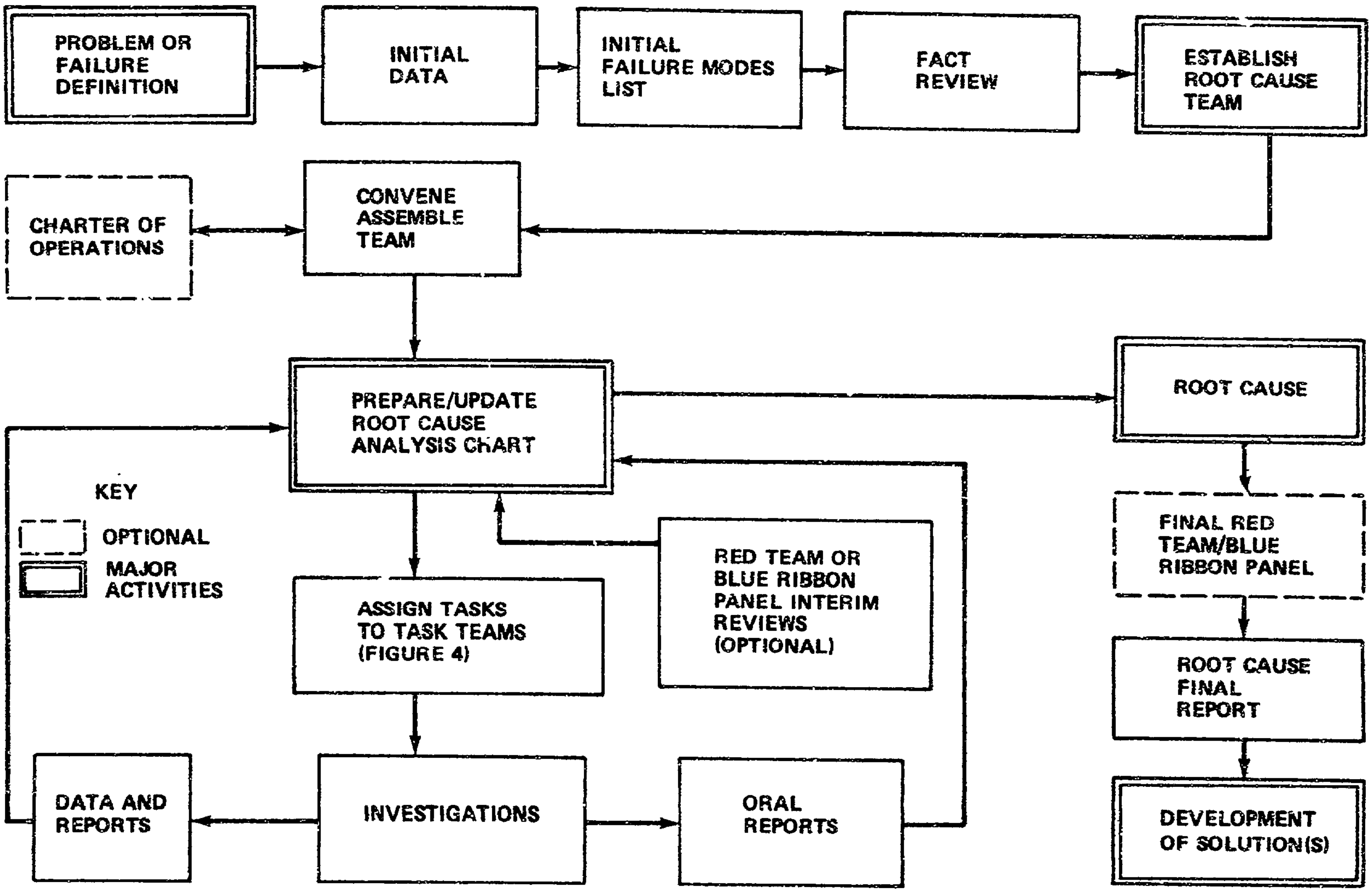

Figure 5. Root cause analysis flow diagram.

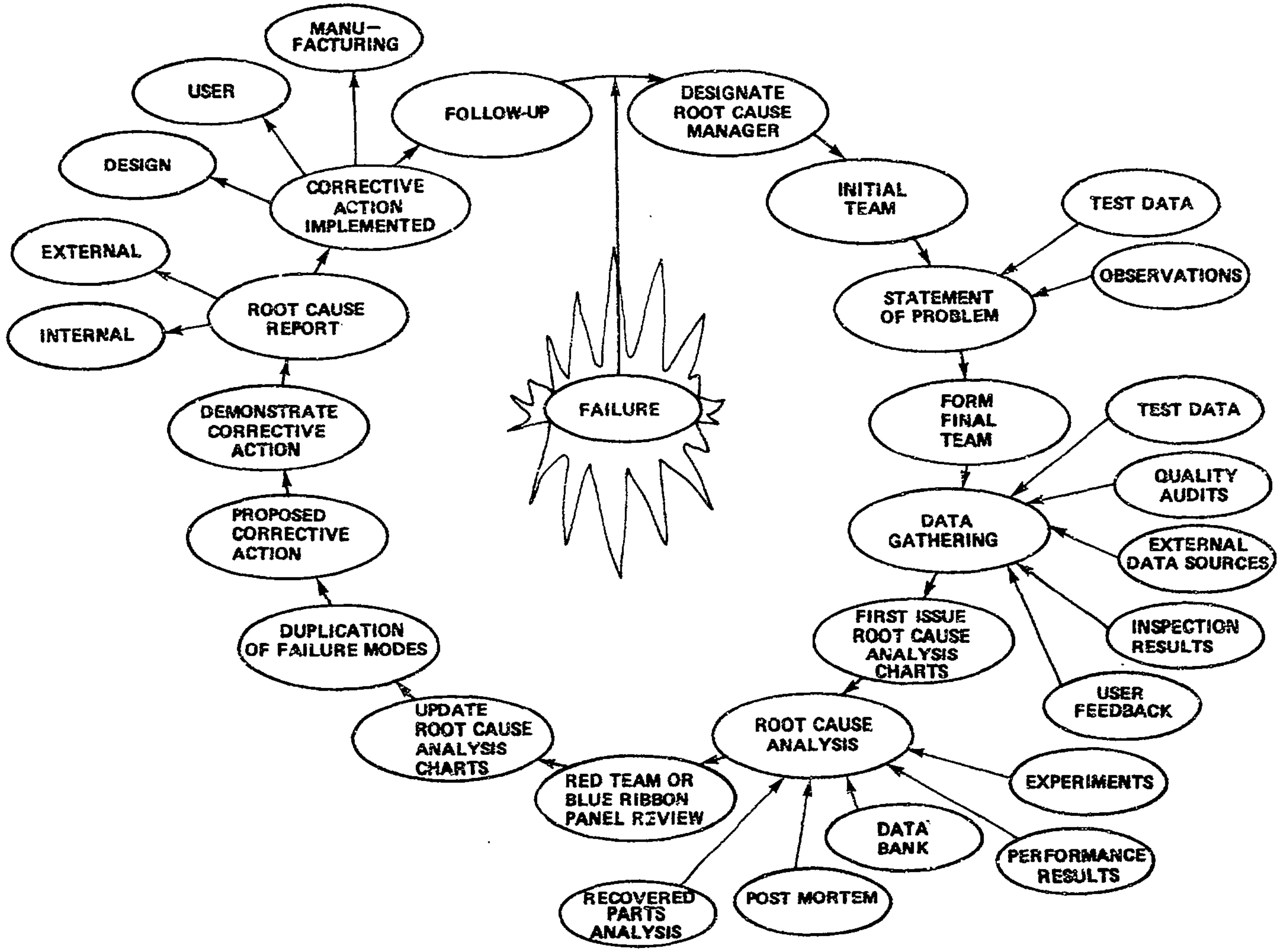

Figure 6. Typical root cause analysis cycle.

It does not matter what the source of the data is (sales reports, instrumentation data, personnel turnover, excess scrappage, or the stated observations of individuals); it is necessary to challenge those facts as to their validity. It is paramount for a manager or investigator to know the difference between the facts available and the assumptions.

In the missile business, the sources of data useful in establishing facts relative to a failure are numerous. Some of the data will be available within moments of the failure, while other data may take weeks to assemble or develop. The data that are available within the first 2 to 3 days after the incident forms the basis upon which the root cause investigation is initiated. The remainder of the data become useful to refute or support particular failure modes. In some cases, new data might suggest previously unidentified failure modes. The following is a listing of some of the key sources of data:

a) Test data — Data taken on specifically measured performance parameters.

b) Telemetry data — Measurements of specific performance parameters of interest.

c) Preliminary test reports — A quick assessment of the test results generally available from the test team in 2 to 3 days. This report will normally provide the history of the test item at the test site and give the conditions and timing of the test, in addition to initial data results.

d) Environmental test results — Often a test is preceded by imposition of required environmental exposures to be expected during the normal life of the test item. Often the environment induced (generally artificially) can produce the condition for failure. The records of the test facility, conditions, and results are essential.

e) Compatibility tests — When an item under test is instrumented, data are taken to assure that the instrumentation has no effect on the item performance and, conversely, that the item under test produces no unwanted feedback into the recording system.

f) Preflight test results — Generally there are checkout tests run on the item prior to the actual test to assure that the item is performing prior to test and to verify that all of the instrumentation systems are functioning normally. The data from these tests can produce interesting facts about the validity of the test at its initiation.

Generally, these are the type data that must be verified before a valid statement of the problem can be made. Some considerations for establishing the validity of the data involved in a problem are presented in the following paragraphs.

Often, more than one type of instrumentation system or technique is used to record a given performance parameter. An example might be the use of fixed cameras, cinetheodolites, radar, and Doppler velocity and position (DOVAP) systems for determining in-flight acceleration, velocity, position, heading, etc. The accuracy and reliability of some of these measuring techniques is greater than others. These factors must be known and considered when the data are compared so that the data (facts) used are those in which the highest confidence can be placed. If data from several sources compare within the limits of the various accuracies, the data can be considered verified.

In some cases it may be necessary to conduct specific experiments to establish the accuracy of data from a given source. Competent test activities establish these values and document them as a matter of facility record. When the application is special, the data accuracy should be a matter of specific note. It is in this area that we sometimes find ourselves doing verification experiments "after the fact."

Where computer simulations of the item under test are available, a particularly valuable verification capability exists. It is possible with this tool to put recorded performance into the simulator to see if the resulting simulation produces the same results as did the item under test. For example, if an engine pressure was telemetered as being low for 20 seconds, would that data "fact" produce a trajectory and impact like that observed on radar or DOVAP? The simulator can provide the answer and thereby resolve any questions about the validity of the engine pressure data.

The accuracy with which a problem can be understood is not likely to be better than the accuracy of the facts. Therefore, it is important to validate the data so that it can be confidently regarded as fact. Make note of data "assumed" to be fact, but take the steps to perfrom tests or analysis to eliminate the assumption at the earliest practicable time.

g) Other sources of data – There are many additional sources of data which may produce facts useful during a root cause analysis. Each fact can be applied to the supporting or refuting data columns of the root cause analysis chart to help establish the root cause mode of failure. Some of the sources of data are as follows:

1) Manufacturing records

2) Assembly instructions

3) Inspection data

4) Quality assurance data

5) Reject reports

6) Waivers and deviations

7) Critical component data

8) Laboratory simulations

9) Previous test reports

10) Historical failure summaries

11) Failure history data banks.

Although the preceding list is not all inclusive, it serves to show that there are many sources of applicable data that may provide insights and facts when performing a root cause analysis.

Use verified data from all available sources. Take steps to verify all data used as rapidly as possible. Be sure to record assumptions and unverified data as they are, so that they do not become confused with facts. Do not discard data as invalid without proving that the data are incorrect. Data are always communicating with us: it shouts, it whispers, and one must be alert and perceptive enough to recognize its message.

5. Root Cause Team Management

How often have you participated in a trouble shooting team to solve a technical problem? How many times have you been selected to lead a trouble shooting team? Those who have infrequently participated in either activity will find the procedures described in this section useful in trouble shooting, and those who have more experience will find techniques which will apply to leading trouble shooting teams.

In the past, the classical role of trouble shooter was played by an individual who detected the cause and solved the problem. Frequently, the engineering trouble shooter was a legend in his area of technical expertise. This was the individual who could be relied on to get an emergency situation under control and his knowledge of the technical area and his tools were all that were required to solve the problem.

Analysis of faults in the space age era is much more complex, many diverse skills are required and often large teams are assembled to solve technical problems. In addition to the complexity of the technical problems are the problems related to the personality differences and the different objectives of those selected to solve the problem. The chairmen of the failure analysis groups frequently are not experienced in more than one technological area which may have bearing on the problem and must, therefore, rely on the help of key members from the team to actually perform the analysis.

What then is the role of this team leader? One view which seems clear is that the failure analysis leader will direct activities of a team of recognized specialists who are frequently brought together on an ad hoc basis and have not previously worked together. The team leader must consider the social environment of the team as equally important as their technical skills, and he must operate in a way which produces a series of rewards to the team as their activities progress.

a. Task Events Aided by Social Dimensions

The analysis of failures by groups is a task event and the job to be accomplished is often a new one to most groups. The groups are frequently ad hoc gatherings brought together for the duration of the problem and, for many of the members, it is the first time they have worked together. The sense of urgency to find an answer may cause a great deal of anxiety. The stress on the productivity of the group is uppermost in the minds of the managers, but the social dimensions of the group can greatly influence progress.

A major task of the group leader is the building of cohesiveness which results in a tightly knit team which helps one another. The loyalty and productivity of the team are closely related to the communication among the members and the social dimensions of the group, in large measure, forms the foundation for a reward system based on feedback among the members. The participant's sense of satisfaction and worth based on his participation are often the only reward for long hours, frequent frustration, and incessant management pressure to get to the root of the problem. Therefore, the care and feeding of the social dimensions of the group are essential early actions which must be addressed. Personal experience shows that the failure of some groups could be traced to ignoring this first step. The failure of the group was not in failing to solve the problem, but in the long time taken to solve the problem and the feeling of dissatisfaction when it was completed.

b. People

Troubleshooting involves individual effort and the exchange of ideas among team members directed toward discovering the root cause of failure. The team brought together in fault analysis sessions will often be a heterogeneous group of individuals with many varied personalities, characters, and emotions. The response of these individuals can be disorganized, haphazard, and chaotic, or the response can be reasonable and rational depending on group interation, leadership, and personal need.

Root cause analysis requires the management of a team, with as few blocks as possible, to produce an open-minded atmosphere which leads to a choice among many alternates to facilitate the essential spirit of inquiry. Participants who are able to operate creatively will have the best chance of discovering the subtle and hidden problems. Stress producing situations are detrimental to creative performance and the leader's task is to enhance creativity by removing or minimizing divisiveness.

There is another school of thought relative to stress. There are those who espouse, and practice with some success, the idea that exceptional people under stress do exceptional work and that average people drop by the wayside. Therefore, it follows that if stress is produced by management you will get exceptional work out of the exceptional people and the average people will be or become nonproductive. Since it can be argued that exceptional people are exceptional anyway, and that there are more average people (who can make real contributions) than exceptional people, stress applied by management serves no real purpose other than to eliminate the contributory potential of the average people. Observation of organizations where this type philosophy is applied shows a high personnel turnover and an atmosphere of general anxiety.

Constant, long term stress is counterproductive. Stress for a short period, if sensibly applied to drive realistic understandable deadlines that are made known to the group under stress, often proves beneficial. Interpersonal stress has no useful purpose in root cause investigations.

c. Root Cause Communication Activities

A key point in the conduct of root cause analysis activities is effectively and timely communication and feedback among the participants. Communication is any system of transferring information that affects the way in which people perform their assignments. Included in the term communication is what is said as well as what is perceived. The information flow is a typical organization using one of the following routes: formal, informal, and implicit; in most situations all three operate.

d. Formal Communication

To improve the formal channel of communication, the cause format evolved. It assists the frequent transfer of information and minimizes efforts to stress any one investigator's bias by the use of concise entries which contain the essence of the information. In addition, the brief entries are used to overcome many technologists' hesitancy to write. A major function of the root cause format is to record information provided during informal communications, discussions,

and speculation sessions related to the problem. Thus, it often serves as a convenient recording medium for all the bits and pieces which would otherwise be lost from the investigator's recall. The root cause format is aimed at presenting a case that is believable and gives equal consideration to all estimates of the problem.

The use of the root cause format also combats "information gaps" which often exist among investigators. In many cases, investigators are separated by thousands of miles and the exchange of brief, concise, and uniform formats facilitate the pursuit of the problem or redirects the focus as new facts are discovered. A typical supporting comment from the root cause critique of a battery production problem team is as stated in the following paragraph.

"Root cause format and philosophy allows all investigators an equal opportunity to express themselves and be heard. It makes others aware without depending on rhetoric. It creates an atmosphere of openness to alternative concepts of the problem and serves as a means of providing access to all information available which is related to problems."

The root cause team manager needs to provide access to information in a systematic way without inundating the participants with, what may be to them, irrelevancies. The root cause format also provides a framework for the structure of the problem which can be used as a plan of action as well as a road map for tracking the many activities. Many times during the analysis of failure, investigators assume that all participants have the same information which is available to them. This is not necessarily true in large organizations and in large scale failure analysis situations where many of the participants perform at remote locations from the facility charged with management of the problem.

Effective communication in the analysis of failures must flow simultaneously in two directions. The root cause manager usually has many resources for getting its message to participants, but the only effective method for most participants getting their input considered is via the entries on the root cause format. The importance of establishing an effective communication loop among root cause team members cannot be overstated because it is the primary manner in which facts are detected and distinctions made that ultimately lead to the solution of the problem. The participant's attitude toward information exchange must be continuously nurtured and his contributions must be equally considered. Based on the operation of more than six teams over the last 3 years, it became evident that the progress of the team was related to the attitude of the individuals and the atmosphere which prevailed during the frequent meetings and informal sessions. Solutions were enhanced in root cause teams which had developed an effective internal communications loop. An essential facet of root cause management is the development of communications loops and their maintenance.

e. Informal Communications

Information exchange is enhanced by the proximity of the participants. In a recent study of research and development organizations, it was found that communication among members essentially ceased if they were separated by a distance of 30 meters or more. This fact verifies the empirical findings of many root cause teams, i.e., that much information is exchanged orally due to the organization and location of key members in a "war room" atmosphere.

The number of information exchanges are greater when the structure of the team is given close attention. A few individuals in each root cause team act as technical "gatekeepers" and in essence perform a service of providing internal consulting services to the team. In general, they are good communicators, high technical performers, and are usually visible to all the team members (everyone knows who they are). In addition, they often have long standing relationships with outside experts in their areas of interest and can quickly pinpoint skills or knowledge which should be brought to bear on the problem.

f. Implicit Communication

When new facts or distinctions are uncovered by a small subteam, a sense of adequacy pervades the team which emotionally reassures its members. The emotional rewards lead to positive attitudes which can carry over into other subteams.

The managers of root cause activities must demonstrate an attitude of receptiveness and trust toward the subteam leaders and can continually reinforce these feelings by frequent demonstration of active listening. Actively seeking out team findings and plans nurtures openness and responsiveness.

What managers demonstrate in day-to-day operation implies much more than what they say. Therefore, the image that the root cause management conveys can directly influence the productivity of the participants. The image initially created will persist even when management attitudes are altered. Thus, getting started properly is far more productive than trying to modify attitudes.

g. Prognosis

The use of small teams working together on segments of the problem assures that each member can make contributions which are recognized by the other members and which builds cohesiveness within the team and enhances the chance of developing effective communicator loops. The team leader's job is to nurture openness and provide a mutual sharing of the responsibilities. A subteam size of four to five members is recommended to maximize the communications loop

performance. The small subteam allows the best chance of meeting all of the conditions for fact finding and removing preconceptions and emotions from the team members.

h. Cohesive Activities

Teams which have worked together on a brief intensive basis, frequently in long hours and working more than 5 days, achieve a high level of cohesiveness and an increase in communication feedback usually results. Individuals on the team want to maximize information exchange and strive to inform all team members. In addition, if they do not know, they are more apt to ask information questions because admitting ignorance does not cause them high risk of ridicule from other members.

Cohesive teams are stable teams. Each person's role is defined and his participation is valued by the other members. Members concentrate on the "messages" being conveyed and this improves listening and information transfer.

Cohesiveness can be achieved quickly and maintained if the team manager addresses the way the team is operating and systematically evaluates their group performance. Two aids which give the team manager insight are the use of written critique of performance by members and the presence of feedback from members.

The building of a "team tradition" is a cohesiveness enhancer which usually can be developed in a few days. Many of the root cause teams were nicknamed "Tiger Teams" and evolved symbols or ensignias. The use of a "smiley face" was used effectively to identify Tiger Team members and sticker and rubber stamp smiley faces were placed on reports or correspondence from the team.

Many meetings were held to summarize progress and, in many cases, there were rituals associated with progress such as the presentation of plaques, cartoons, "atta boys" or "atta girls" in an informal manner. In addition to the aiding cohesiveness of the team, the meetings assured that good performance was recognized. The progress meeting became an important part of the social interaction of the team, often addressing the short term reward needs of its members.

i. Evaluation as a Cohesive Force

Cohesiveness and its nurturing requires time and effort during the early life of the team. Do not neglect the planning which increases team effectiveness. In the study of groups, one of the key findings was that groups seldom spend any time talking about the group and how it functions. Groups are sensitive to task performance and thus tend to concentrate on the job and ignore how the team functions.

Team performance is increased when groups spend brief periods talking about what happened during meetings, with special emphasis on what was good about the performance.

Frequently, one individual skilled in group dynamics or group process serves as master evaluator and presents a systematic overview to begin the discussion.

j. Goal Setting

Set clear, attainable group goals. Establishing the root cause of a failure is a long term goal and does not offer success early in the effort on which to build cohesiveness. Goals for a given week or for several days is very likely to produce improved or increased morale. Achieving a goal frequently rewards all members of the group. Daily goals or weekly goals assure ego rewards on a regular basis. To be useful in building cohesiveness, goals must be clearly specified and understood by the team and should have a high probability of being achieved.

Reaching a clear goal is a group reward which is highly visible and can be used to emphasize group identity. Generally, individual rewards are stressed over group rewards in technological organizations, and during root cause activities, group rewards must be stressed as an aid to cohesive building.

k. Rewards

Often the teams formed contain members who are from other organizations and who serve as a means of eliminating parochialism. They are interested in returning to their regular jobs quickly and, in a few cases, they are upset about how their absence would delay the progress of their normal assignments. Cases may arise where team members spend months away from their regular assignments and, in addition, their management becomes dissatisfied over the lengthy separation from the regular assignments. These conditions can be alleviated by recognition and rewards.

A reward system which can be rapidly used, is highly visible, and strengthens the team spirit is an ideal target. Since the duration of the team's lifetime is not predictable, rewards must be provided from the formation of the team. The leader is responsible for the formal and informal award system and, in general, the formal award system only operates after the task is completed. Thus, the importance of informal awards during the on-going task becomes extremely important.

Rewards furnished to each member by the group are essential to generating team cohesiveness. The motivation of the teams must concern itself with the individual needs and how the team performance can provide rewards that satisfy immediate needs. Some examples of rewards typically operating are as follows:

1) Material rewards - Usually are made after-the-fact for exceptional performance and are usually reserved for only a few of the many participants. Money is highly visible but not normally effective during the root cause analysis process.

2) Social rewards - Can be provided during the process and are available to each member during day-to-day activities. The need for respect and appreciation is almost universally felt and the close contacts and interactions in the work situation brought about by the sense of urgency and importance almost always assures that this need will be satisfied if the leader makes provision for frequent recognition of progress and is honest in assessing performance. In many problems of short duration this will be the only reward perceived by the participants.

3) Esteem rewards - Provided for members of the team as it makes progress in solving the problems. The work groups share liberally the esteem of individuals within the group who are responsible for significant activity in getting at the root cause. This reward is especially noted in long term situations where a series of problems is solved before the underlying root cause is established.

4) Work rewards - Can be enhanced as a result of the urgency and attention directed at teams engaged in organized, systematic study of failure. An unprecedented level of visibility is maintained by management. The team members know that their work is significant and that it is being given attention beyond that typical of a routine work assignment; therefore, appreciation given while the job is progressing provides a work satisfaction not normally available and is especially beneficial at points of significant breakthroughs.

1. Process

Root cause analysis is a cooperative group process and if the participants enter the activities on a cooperative basis, there is a strong possibility that the process will bring rapid results. In addition, the common problem, activities, and goals can build a bridge of understanding out of the divergent interests. As in building bridges, the most time consuming and positive activity is at the beginning. The root cause team leader must be able to convert divergent interests into channels of common goals by emphaszing matters that can be agreed upon and not dwelling on points of difference until the fragile early team structure can be strengthened by the day-to-day process of working at new insights.

To summarize, root cause analysis is, by necessity, a cooperative process, and common goals must be established and understood. It is a behavioral process, not solely an exacting science.

6. Practicality of Root Cause Analysis

Practicality! How far does one go in performing root cause analysis? How much money should be invested in such an activity? How long can one afford to wait for the results? The answers to these questions and many more of the same ilk are of great interest to managers. It is obvious that there are no firm answers. That is probably a good situation because if there were firm answers for such questions one might be deceived into thinking that we do not really need managers.

In the absence of "answers," it is appropriate to briefly discuss some of the practical considerations involved in the development of the specific solution to each peculiar problem that the manager faces.

One way to approach the problem is to ask, "how much will it cost if the problem continues unresolved, or the failure recurs?". It might result in the answer that one can afford to spend that much to assure that it is resolved. If it would result in the loss of your business or an entire project, there is an investment or an expected profit that must be protected at some level. The analysis of such tradeoffs are referred to as "risk analysis" which has been discussed in several texts, one of which is Decision Analysis - Introductory Lectures on Choice Under Uncertainty by Howard Raiffa, Addison/Wesley Publishing Company.

Generally, each hardware failure should be thoroughly dealt with during development, i.e., the rationalization of statistical probability should be firmly resisted. This view is particularly valid in development because the statistics are based on small quantities and development is the proper time to determine and eliminate system weaknesses. The greater the expected production quantity and/or rate the more vital it is to assure that failure causes are determined and corrected. The rationalization, "if an item does not cost much per unit, you should not spend much to resolve failures," will not stand the light of day. An entire production run of many individually inexpensive items may prove to be faulty; the total investment for which could be enormous. Fortunately, that false rationalization has not been encountered where high item unit costs are involved. The failure of one such item is patently a problem.

Failures that occur during or after the production phase have a slightly different aspect, or at least they appear to. After a rigorous and thorough development, one might tend to want to view failures and production hardware with the law of probabilities' rationalization, i.e., "there are going to be some." This rationalization is generally aided

and abetted by the fact that there is usually little information or real data obtained from the failure. Practical experience has shown that the same root cause analysis effort should be applied as in development. Because of the lack of firm failure event data, it is often prohibitive from a cost/time standpoint to establish the root cause based on that one event. In such cases, it has proven effective to address the "most probable" modes of failure on subsequent tests, being alert to any indications that would resolve the problem to its root cause. Several incidents of this nature have been dealt with in this manner and ultimately resolved at minimal program cost. Although the solution took time, the formal root cause analysis team was not formally retained beyond the establishment of the most probable failure modes. As soon as more clarifying data became available, the team was reconstituted to complete the root cause analysis.

These practical considerations must be taken in context with one overriding premise, i.e., no failure can be ignored, it will not "go away." The systems manager must address it resolutely and directly. Root cause analysis is a systematic technique for the attack and positive resolution of such problems.

Appendix A.

FLIGHT 162 INCIDENT REPORT

Prepared by	Reviewed by	Approved by
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1.0 SUMMARY

LANCE Missile 2175 (Flight 162) was fired on 3 August 1972. The missile was the first of the Management Reserve rounds. The preflight sequencing was normal until about 1.6 seconds after fire command. At that time, a transient on the missile power battery occurred, followed by a premature closure of both BTV's. With only the sustainer engine operative, the missile performed a very short 3.7-second flight, impacting 50 yards downrange.

Extensive tests and analysis have isolated the root cause to be the inability of the power battery to handle current loads just after initiation, due to the high internal impedance at this time. Simulator tests using a 29 ohm load in series with the power battery to simulate the high internal impedance reproduces the flight failure. Comparison of the simulator TM records with the flight records duplicates all flight characteristics:

a. Premature BECO

b. Boost Good Guidance inhibited

c. MTS shutdown

d. All electrical transients similar to flight.

To ensure that the power battery internal impedance is sufficiently low to ensure the loading capability, the following corrective actions were taken, starting with Flight 163:

a. Initiate the power battery under a 15 ohm load

b. Provide a more positive indication of umbilical disconnect by modifying the power interlock circuitry in the M/P.

2.0 FLIGHT DESCRIPTION

2.1 Summary

LANCE Missile 2175 (Flight 162) was fired at 0815 hours (MDT) on 3 August 1972 from an LZL located at L-350A, an east launch point of Launch Complex 33. The missile was the first of the Management Reserve rounds, incorporating an alternate Sunstrand accelerometer and a piggyback ballasthead with three Honeywell airbearing gyros, and was programmed to a maximum range impact (T + 1.6 km). The preflight sequencing was normal until about 1.6 seconds after fire command. At that time, a transient on the internal power battery occurred, followed by a premature closing of both BTV's. When the feed system pressurized about 0.2 second later, only the sustainer engine fired. With the order of magnitude less thrust, while the spin and vent systems operated normally, the missile performed a very short 3.7-second flight, hitting the launcher in leaving and impacting about 50 yards downrange. The tankage remained intact and the sustainer engine continued to operate to propellant exhaustion.

2.2 Test Configuration

A. Ground Support Equipment (GSE)

The launcher was a Tactical Prototype LZL emplaced with zero slope, zero cant, and zero traverse at L-350A, an east launch point of Launch Complex 33, White Sands Missile Range, New Mexico. The launcher was not restrained with any tie-downs and was sighted and layed to a quadrant elevation of 54° and an azimuth of 0.4376° east of WSTM Grid North.

B. Missile Configuration

The missile configuration consisted of an ET/ST tank body assembly, a five-ring "C" casting engine system, and PRM G&C package which utilized an alternate source Sunstrand accelerometer. The large honeycomb fins were modified to include structural skin reinforcements, and the System V instrumentation package was modified to measure boat-tail temperatures and performance of the three piggyback "airbearing" Honeywell gyros.

2.3 Pre-Test Operations

Missile 2175 was selected from the ARMTE WSMR Rounds. The missile was processed by ARMTE through an initial inspection (I1) on 30 March 1972. The missile was not cycled through any preflight ET or ST environments. The missile was instrumented at WSMR with a Type V telemetry system and processed through I4 on 20 July 1972 for firing on 25 July.

A Flight Readiness Check (FRC) on 24 July revealed that the gyro yaw null was drifting and the missile was returned to the Assembly Building. The gyro was replaced and a second I4 was performed on 27 July 1972. An FRC was held on 2 August 1972 with no problems. The Terminal Countdown on 3 August 1972 was normal until the premature BTV operation.

The VCE on Missile 2175 was recycled for Cg screening on 19 May 1972 and replaced on 5 June 1972. The Systron Donner accelerometer was replaced on 20 July 1972 by the flight Sunstrand accelerometer.

2.4 Test Event Description

All prelaunch checks and data appeared normal until 2.35 seconds (Range Time), at which time the missile power battery indicated a drop in voltage. The following is the sequence of events from telemetry data:

a. Fire command - (0815 hours) 0.816 second

b. Fire logic enable - 0.832 second

c. Piggyback gyro relay - 1.917 seconds

d. Power transfer relay - 2.280 seconds

e. Pitch and yaw memory - 2.288 seconds

f. Gyro spin rate sensor - 2.353 seconds

g. 0° - 180° TVC voltage dropped from 28.8 V to 6.2 V

h. 90° - 270° TVC voltage dropped from 28.8 V to 7.8 V

2.35 seconds

i. MTS cut-off - 2.364 seconds

j. +22 VDC PSE voltage dropped from 22.35 V to 14.9 V

k. Integrator voltage dropped from 16.2 V to 7.4 V

2.38 seconds

l. 90° - 270° TVC voltage recovered to 13.5 V and started increase to steady state - 2.395 seconds

m. 0° - 180° TVC voltage recovered to 16.7 V and started increase to steady state - 2.403 seconds

n. Pulse battery voltage dropped from -28.5 V to -25.3 V

o. Power battery voltage dropped from 28.8 V to 17.6 V

2.41 ± 0.167 seconds (Commutated channel)

p. First motion - 2.613 seconds

q. Five-inch travel - 2.828 seconds.

The BTV's were prematurely commanded which resulted in sustainer-only operation. The following film review provides the sequence of events.

2.5 Film Review

Approximately 100 minutes of film were viewed. This consisted of regular and high speed film.

At ignition it appeared that only the sustainer ignited. Venting was very heavy. The missile moved forward relatively slow and first rotated approximately 5° to 10° to the left and then started rotating to the right (clockwise). Approximately half way up to the launch truss the missile appeared to fall on the truss and pitch over sharply. It then cleared the launcher and spun up to a fairly high rate.

None of the film viewed showed the missile striking the ground due to camera placement and smoke obscurement.

When the smoke cleared, the sustainer appeared to burn normally for several seconds. Suddenly long yellow flames came from the nozzle and then the flame died down, followed by approximately 20 to 30 seconds of almost pure IRFNA with little or no flame present. The IRFNA suddenly stopped and a large billowy flame appeared and burned for 2 or 3 minutes. This flame slowly subsided and burned out.

The missile impacted north of the launcher approximately 50 yards. Post-flight inspection of the launcher revealed.

a. Tip of fin No. 1 (white) sheared off on left side of elevation hand-wheel torque tube.

b. Tip of fin No. 4 (red) sheared off on right side of elevation hand-wheel torque tube. No damage to hand wheel torque tube other than the paint.

c. Paint damage at three places on launch truss (center beam) where missile scraped as it cleared the launcher.

2.6 Post-Test Investigations

A. Pad Checkout

The following is the sequence of events which occurred at LC-33 prior to and including G&C package and engine removal on 4 August 1972:

1010 hours - Inspection of ballasthead to tankage electrical connections revealed:

1. Warhead connector P1 from the G&C package to ballasthead intact and connected. When disconnected, both male and female connectors in very good condition.
2. Instrumentation umbilical connector at Station 100 had all pins and wiring pulled out due to impact.
3. Instrumentation connector P2 which connects to G&C still connected but all wiring pulled out of P2 by impact.
4. Instrumentation connector P1 was pulled loose from and broke the connector latching dogs on its mating connector at Station 100.
5. Beacon antenna coax cable pulled out of connector.

1020 hours - Placing of missile and ballast head on dollies initiated. Missile moved and oxidizer and fuel tanks flushed out with water for personnel safety. Boattail cover (O-jive) removed for inspection. Instrumentation connector P2 was removed from G&C J5. J5 in good condition, P2 shows obvious damage from having wiring pulled out. Power battery has dent, apparently caused by being hit by

ballasthead swing bolt. Instrumentation connector J1 at Station 100 removed from bracket, and bracket removed. G&C umbilical connector has two small chips on phenolic insert adjacent to pins U and G.

NOTE: All G&C connectors mated properly with locking dogs visible through inspection holes.

The instrumentation measurement points, G&C J5-AA to J5-HH, for power battery monitor were used to check for diode action (70 ohms one way and 165 ohms with polarity reversed).

Boattail inspection shows the following:

1. All connectors connected.
2. Engine and instrumentation harnesses well charred.
3. Fuel and oxidizer BTV squibs were checked and gave open circuit indications.
4. TVC valve coils were checked for resistance, and values obtained were:

   0° valve - 3 megohms
   90° valve - 20 Kohms
   180° valve - Open circuit
   270° valve - 600 Kohms

Pictorial documentation was obtained on boattail, engine, and G&C compartment prior to removal.

The G&C package was removed from G&C compartment, inspected, and component serial numbers verified. The power battery connectors in good condition when demated. Battery squib resistance measured at pins J to K gave an open circuit and battery output resistance at pins B to F gave an open circuit.

Power battery removed from G&C package for shipment and analysis.

The G&C package was transported to MAB 13 for further checks.

TVC valves were removed from the engine, decontaminated with water, and transported to the Q-Hut area for further tests.

The engine was removed, flushed with water to decontaminate, and taken to MAB 13 area and stored in a properly secured area.

The tankage was stored at LC-33 inside the locked conditioning shroud.

The TVC coil resistance measured at the Q-Hut after connectors were removed were all approximately 37 ohms, and open circuit to case. The connectors were removed because fire damage prevented coil resistance measurement at connector pins.

MTS/LCC check - MTS 10 and Pad wiring in post-flight Missile 2175 configuration. No problems were encountered and proper operation was verified.

B. Action Taken on the G&C Package and Associated G&C Connections.

1. A physical check was made of the power battery connector both prior to and after demating to the power battery. The connector and all the pins on both mates looked normal with no indications of physical damage or excessive current damage. A check of the power battery load readings into the instrumentation connector (J5) resulted in a reading of 70 ohms. The J5 connector was checked and appeared normal with no signs of physical or overcurrent damage. This passive resistance value is satisfactory for a shutdown package. The battery load becomes more nearly 35 ohms during power up, however, the 70 ohms was indicative that no shorts or excessive load existed.

2. The remaining G&C connectors were also physically checked prior to and after demating. All other G&C connectors looked normal with no signs of damage.

3. The G&C package was removed and came off easily with the only visible signs of physical damage being one small indentation being observed on the power battery. The indentation was caused by the ballasthead lag bolt that bumped against the battery case during the missile impact and ballasthead breakaway. The power battery was removed and expedited for immediate hand-carry to Eagle-Picher.

4. The boattail cover was removed and engine harness continuity checks were attempted but the harness readings were of little value due to the severe burning that took place inside the boattail. All the harnesses inside the boattail were badly burned and charred. The only conclusive readings were of the BTV squibs. The BTV squibs read open when measured directly at the BTV connector pins. The TVC's were removed to test the TVC coil resistance. Readings could not be made on the installed TVC's because all the TVC connectors were severely burned such that the pins and connector inserts were falling off. The TVC's had the connectors removed at the electronics lab where then the TVC coils gave resistance readings of 37 ohms and open circuit readings between the TVC coils and the TVC metal housing. Therefore, it was concluded that the TVC resistances were satisfactory and would not cause of possible shorts or excessive loading.

5. Functional checkout of the G&C Package - The G&C package was taken to the MAB to troubleshoot for excessive power loading of the

power battery circuit. The power hook-up to the G&C package was done in the cautiously prescribed manner of applying a power connection only to the G&C package at the power battery connector. Power was turned on (129 volts) and the current was measured to be 890 milliamps. This gave satisfactory indications that no overload problem existed in the G&C package. The G&C package was then hooked up to the SCC in a normal package level set-up as per VMRC-M Procedure 1-00A-130. The checkout was initiated with one modification being required to perform the test; a caged workhorse gyro was substituted to perform the RCK tests. The checkout was performed satisfactorily through 10 with no problems; that is, the PRE and RCK checkouts were satisfactory. However, a problem was encountered during the very first portion of Paragraph 11 which tests the VCF. The problem encountered represented a malfunction in the VCF rapid charge circuit. The package checkout was discontinued at this point since a joint discussion with the task team personnel resulted in a decision to ship the package to LIVAC-M where detailed testing was performed.

6. The rapid charge circuit malfunction was attributed to missile impact and was not present during any preflight checks and certainly not during the flight operation. The function of the rapid charge circuit is to implement the charging of the integrator during the first 10 seconds of monitor programmer preset or launch modes. The rapid charge circuit always performed the expected charging function during the monitor programmer cycles.

C. Condition of Ballasthead PB5 After Recovery

1. Ballasthead PB5 was picked up from impact point at LC-33 area. The nose cone antenna was broken off at about the midpoint on the cone. The missing half was found on the ground without the VHF antenna tip. The instrumentation umbilical connector wires were completely pulled out of the connector shell. The G&C signal plug was in the same condition as well as the beacon antenna coax cable which separated at the plug that mates to the power divider. The only plug which remained intact was the warhead connector.

2. Upon return of the head to the MAB, the skin was thoroughly cleaned prior to removal. A continuity check was then performed of the XM811E4 (Mod), S/N 460, timer. This test showed that the BECO and SECO squibs had been fired. A visual inspection of the timer showed the following settings:

ARM	to	80
S/A	to	GREEN (Safe Indication)
SCO	to	OFF
X100	to	1
X10	to	4
X1	to	0
X.1	to	0

These readings were verified by the Honeywell Representative in his lab and he stated that the time was, in fact, 140.009 seconds (as expected) that a BECO signal was received while the missile was on the ground and that the 140 seconds had rundown, however, the timer remained in the GREEN position because of the lack of thrust acceleration. The telemetry did not show these functions because of its early failure.

3. No further damage was noted inside the head. All the telemetry components appeared in good physical condition. No operational test was performed at this time because of damaged wiring described above. The gyro cage was removed and shipped to LTVAC-M including the three Honeywell gyros whose squibs were in fact fired. This cage also includes the MARS package. The TM and Beacon batteries were removed and stored in the lab. Also, the VEGA 302C Beacon and DOVAP components were removed for return to Government personnel.

D. Engine Condition After Recovery

Engine inspection revealed that both STV's were closed and the booster chamber showed no indication of ignition. The aft bulkhead showed the APU locked in the open position and the oxidizer burst diaphragm properly open. The sustainer engine showed a burn through to the booster at 0°.

E. VCE Checks at LTVAC-M

The VCE used in this missile, VCE S/N 1197, was recycled to LTVAC-M in May and received the screening tests instituted as a verification of the precision resistor networks. These tests included thermal shock, combined temperature/shock and temperature/vibration testing at +200°F and -40°F. Prior to these tests and subsequent to their completion, the VCE was tested on the G&C SAIE which includes a complete check of the power switch and one-shot. The VCE was returned to WSMR and reinstalled in the missile following the successful completion of all tests.

3.0 DATA EVALUATION

The most significant telemetry and hardwire van data are reproduced in Figure A-1. Examination of telemetry tapes and the hardwire van records were made with emphasis on developing a time sequence of the events depicted. All events appeared normal until approximately 70 msec after power transfer at which time a series of transients were observed which suggest the sequence illustrated in Figure A-2.

3.1 Postulated Failure Sequence

The firing of the missile gyro is controlled by the pitch and yaw nulls, the pulse battery sensor and power transfer with power transfer normally being the latest in time. Following power transfer, the gyro

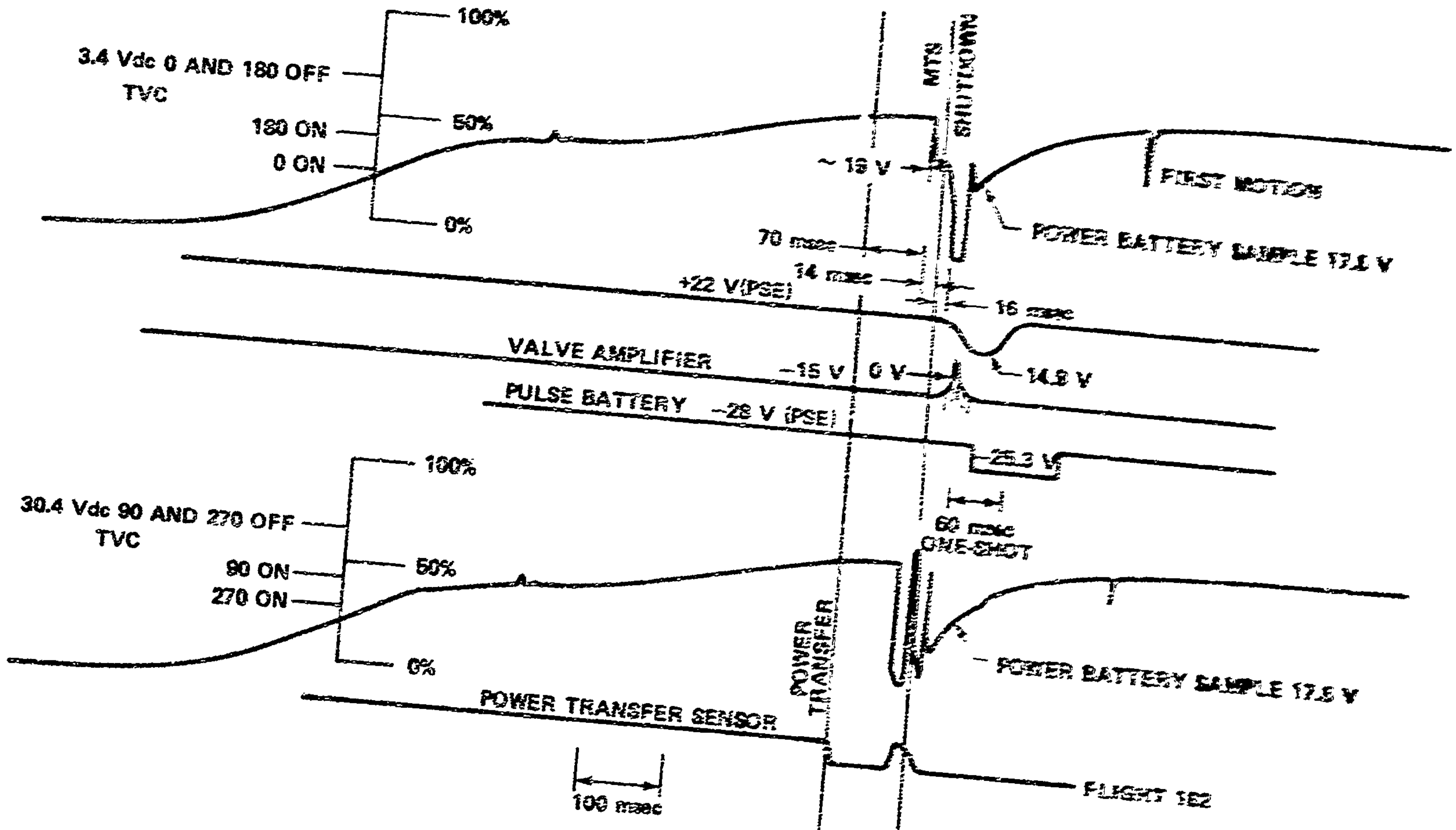


Figure A-1. Flight 162 launch data.

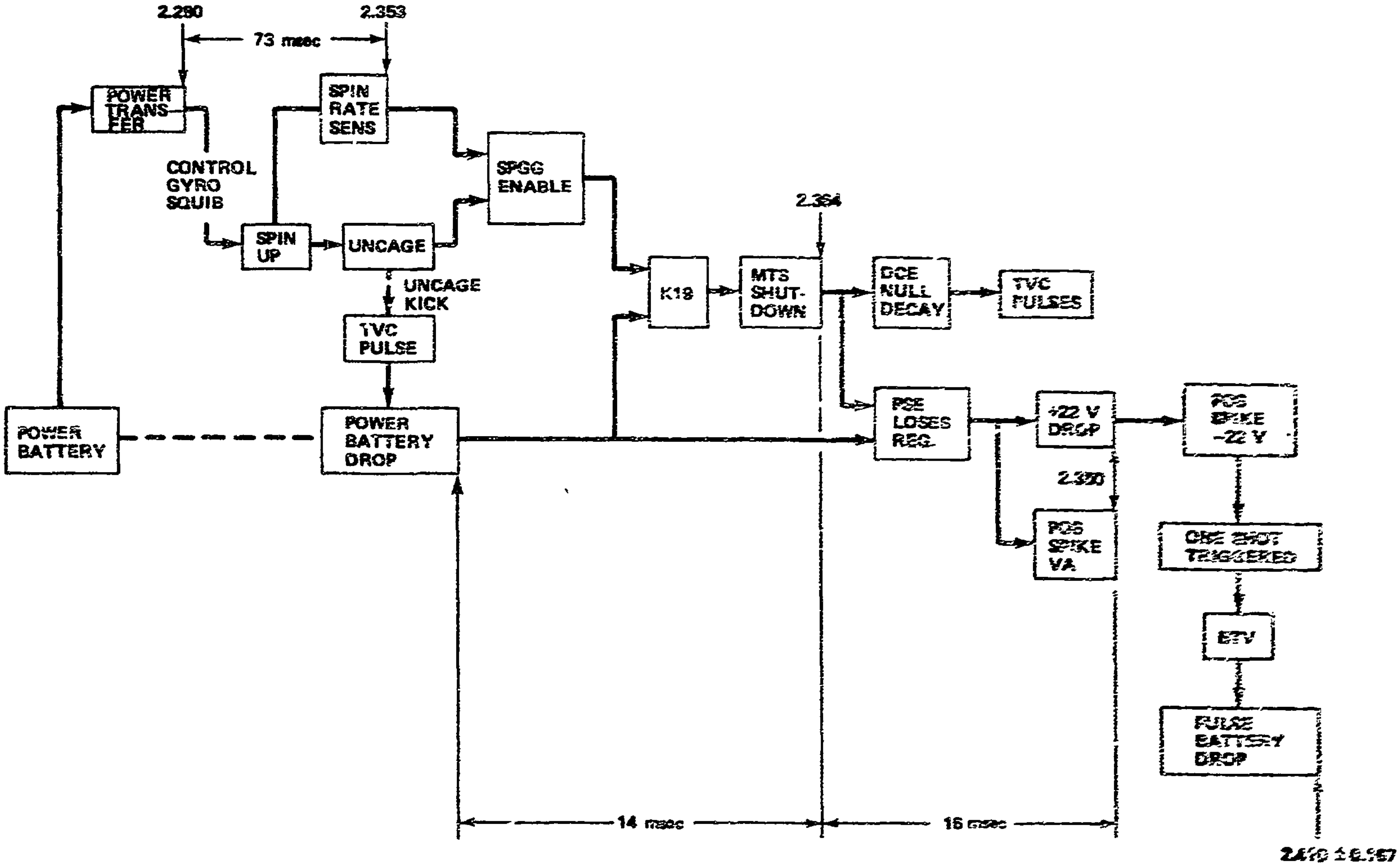


Figure A-2. Flight 162 failure sequence.

squib relay is energized and the squib is initiated by ground power. Following spin-up and uncage, the gyro monitor event and the spin rate sensor are required to initiate the SPGG relay. The 73 msec time delay between power transfer and spin rate sensor event is indicative of proper operation of the MTS launch sequence to this point.

Approximately 2 to 3 msec prior to spin rate sensor event, a TVC pulse is generated. This pulse may be due to a gyro uncage kick. TVC pulses have been observed on previous flights prior to first motion. Simultaneously with the TVC pulse, the power battery output, as observed on the other channel's TVC, was reduced below the GSE battery level. The circuitry of interest is shown in Figure A-3.

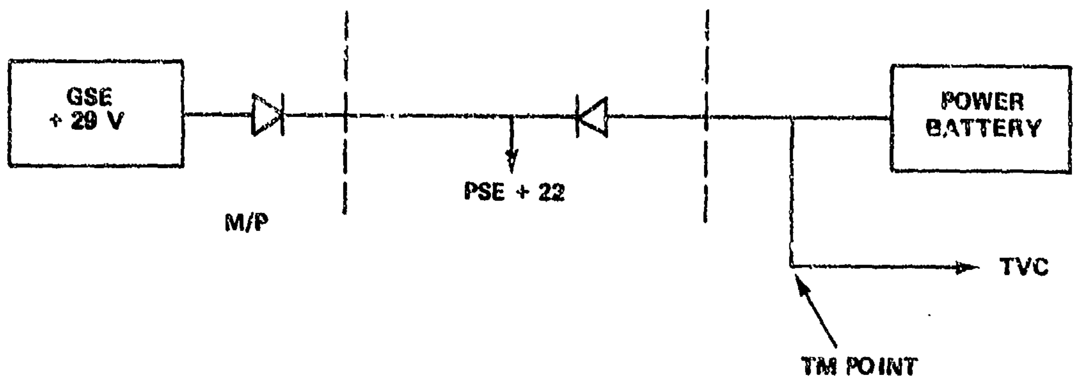


Figure A-3. Missile primary power.

Note that the PSE will be supplied power by either the power battery or GSE power depending on which source has the highest voltage level. Thus, when the power battery output is reduced when the TVC pulse is generated, the MTS will keep the PSE functioning and the power transfer sensor will switch back to its original state. During this period, the SPGG relay is initiated (within milliseconds of the spin rate sensor event). This relay closure during the period when the power transfer sensor is indicating the missile power drop results in the initiation of the power interlock relay in the MTS. (This event normally occurs at umbilical disconnect.) This results in the complete shutdown of MTS regulated power. The hardwire records show this event occurring 11 msec after spin rate sensor event which is normally the pick-up time of the SPGG and interlock relays.

The loss of MTS power results in the reduced output of the power battery assuming the entire load of the PSE which further reduces its output. The power battery output on TM shows the output beginning to recover when the 12 msec minimum TVC pulse is gone. Approximately 2 msec later, the output is dragged down below the previous drop, which correlates with the 14-msec interval between the beginning of power drop and shutdown of the MTS.

Loss of MTS power renders the PRM null loop inoperative which results in TVC pulses on pitch and yaw. The sequence of events to this point is identical to Flight 153 with the exception of the severity of the power battery drop. On Flight 153, the output was reduced to 24.7 volts which was sufficient to maintain regulation of the PSE +22 volt supply. On this flight, the drop was well below the value required for regulation (on the order of 23.5 volts required to regulate the +22 volts versus an observed +17.6 volts). As a result, a large electrical transient was introduced into the missile power system with regulation lost. The +22 VDC output of the PSE drops to 14.9 volts approximately 16 msec after MTS shutdown. All other missile power is derived from the +22 volts and will experience similar transients. The circuitry of interest is shown in Figure A-4.

The removal of MTS power turns off the Boost Comparator Reset signal to the VCE but a time delay keeps the transistor switch on for approximately 125 msec, which is well beyond the time frame being considered. Simulator tests have shown that the BCR time delay keeps the zero-crossing detector disabled during the electrical transients. The plus boost termination output of the VCE which provides an input to the Boost Good Guidance circuitry is disabled during this time frame.

The -22 Vdc supply which is derived from the +22 Vdc supply exhibits a positive-going transient toward zero. This positive spike couples through the one-shot timing capacitor to trigger the one-shot for 60 msec which fires the BTV squibs through the power switch.

The 7 Vac, 4 kHz supply is also derived from +22 Vdc and drops toward zero. This transient triggers the DCE detection circuits which inhibits the Boost Good Guidance SCR and cuts off the TVC valves.

3.2 Other Possible Failure Modes

Although a transient due to loading the power battery right after activation when its internal impedance is still high appears to be the most probable cause of the failure on Flight 162, a number of other possible failure modes have also been evaluated. In this section, each of these potential causes of failure are described together with the data or information available to confirm or refute them.

A. Shorted VCE Power Switch

Since the output from the pulse battery is used to fire the BTV squibs through the VCE power switch, a shorted transistor in the switch would allow the squibs to be fired when the pulse battery comes up to power. This normally occurs less than 1 second after activation. Examination of the telemetry records which are commutated at 8 samples per second shows no evidence of a drain on the pulse battery until 1.6 seconds after activation. While this does not prove that the battery was not loaded down earlier, it does strongly support that it did not and hence that there were no shorts in the VCE power switch.

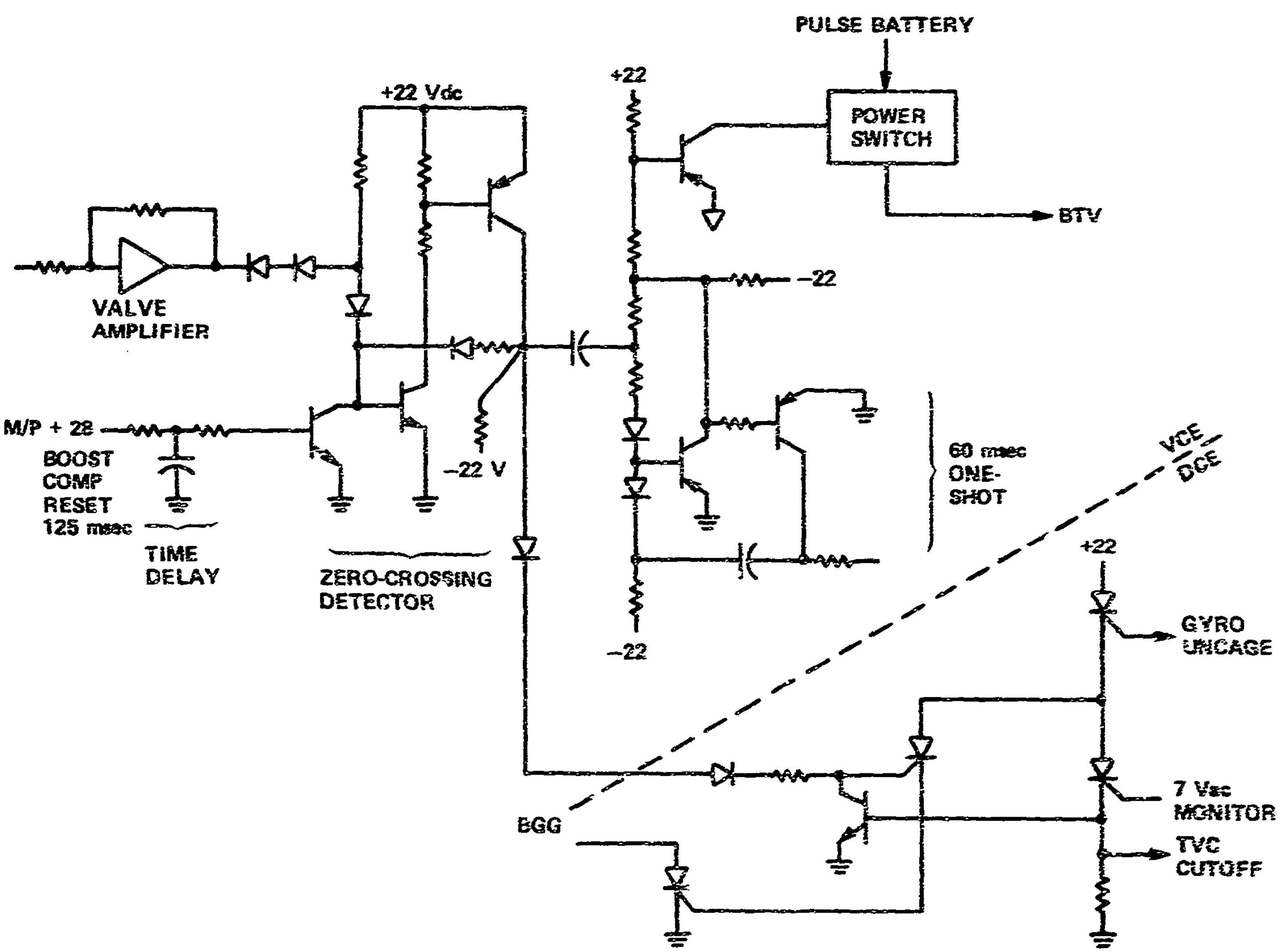


Figure A-4. BGG/BTV interface.

B. Failed Accelerometer, VCE Integrator or VCE Valve Amplifier

Component failures which caused positive saturation of the Sunstrand accelerometer or the VCE valve amplifier or negative saturation of the VCE integrator could cause the integrator to run down very rapidly thereby potentially firing the BTV squibs early. Analysis of the VCE circuits shows that such failures would have caused the sustainer to shut down and would have transmitted a boost good guidance signal. Since neither of these things happened, it may be concluded that failures in these items did not cause the Flight 162 failure.

C. Shorted TVC Valve, Engine Harness, External Harness, G&C Harness or DCE

A short in the circuit leading to the 90° TVC valve which experienced the first TVC pulse on Flight 162 could have caused an excessive current drain and hence voltage drop on the power battery. Post-test impedance measurements on the four TVC valves gave readings of 37 ohms which is within specification. Post-test functional checkout of the G&C package showed the DC system to operate manually. Unfortunately, test damage prevented continuity measurements of the engine and external harnesses. Telemetry records, however, show the normal impedance kick on 3 of the 4 valves which received DCE commands (including the 90° valve). It can therefore be concluded that anomalies in the TVC circuits did not cause the Flight 162 failure.

D. Shorted Diode in the MTS

A shorted diode on the MTS missile power output could have allowed a substantial drain on the power battery when the MTS power shut down 1.6 seconds after fire signal, thus causing the power transients described previously. A post-test checkout of the MTS showed it and the diode to be functioning normally, thus eliminating this as a cause of the Flight 162 failure.

E. Shorted-Power Supply Electronics (PSE)

A short in the PSE at 1.6 seconds could have drained the power battery causing the power transients, etc. Post-test functional checkout of the G&C package showed the PSE to be functioning normally, thus refuting this potential failure mode.

F. Pad Wiring - MTS Monitoring Circuits Plus the Recent Time Delay Mod

An anomaly in the pad wiring, particularly in the MTS monitoring circuits could have caused the drain on the power battery, etc. Post-test pad checkout showed that all pad wiring functioned properly, thus refuting this failure mode. In addition, there was no connection bet ·en the power source of the time delay mod and the power associated wit the launch sequence.

G. XM811 Timer Signal

A premature signal from the XM811 timer caused both an early SECO and BECO. Since the sustainer engine continued to operate normally and since telemetry records show no evidence of a good guidance signal to initiate the timer, there is no possibility that this failure mode could have caused the Flight 162 failure. The fact that the timer squibs were found fired on inspection after impact and loss of telemetry signal is not understood, but is not part of the basic Flight 162 failure.

H. Instrumentation Interface

A short in the instrumentation could cause a drain on the power battery, etc., or saturation on the integrator or valve amplifier in the VCE which caused the early BECO. However, all TM records show normal functioning with no evidence of a short. Further, all TM monitoring points are current limited.

3.3 Failure Mode Summary

Table A-1 presents a summary of all potential failure modes with the supporting and refuting data.

4.0 DIAGNOSTIC EVALUATION AND TESTING

Post-test inspection of missile and GSE hardware, plus analysis of telemetry and hardwire van data, showed that neither the new accelerometer not gyros were the cause of the failure. Instead it strongly appeared that the premature firing of the BTV squibs was due to the loss of power regulation by the PSE, as a result of the power transient on the power battery. The power battery transient appeared to be due to a current drain on the battery due to an early high battery impedance during the first TVC valve pulses. Therefore, the diagnostic evaluation outline was as follows:

a. Review launch sequence of previous flights

b. What can cause TVC pulsing prior to first motion?

c. Determine time history of power battery internal impedance after activation

d. Was the battery used in this flight typical of previous flight batteries?

e. Determine the effect of power transients on the G&C system.

4.1 Launch Sequence Review

Previous flight records were reviewed to determine if any evidence of launch sequence anomalies could provide a background to the postulated

TABLE A-1. SUMMARY OF POTENTIAL FAILURE MODES

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION

CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
Shorted VCE power switch.	Shorted transistor fires RTV at pulse battery activation.	None	Functional checkout of power switch at LTVAC-M no evidence of pulse battery drain at activation on TM records.	None.

CORRECTIVE ACTION: NONE X (CHECK ONE)
REQUIRED

CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
Failed accelerometer.	Accel saturates positive driving integ to zero and triggers BTV.	None.	TM record shows no saturation; run down with 60 Vdc output saturation would require 0.9 sec, no TM record of integ run down; saturated output would shut down sustainer and give BGG signal, and TM records show full-on sustainer signal and no BGG signal; films show sustainer full-on; G&C SAIE shows accelerometer is functional.	None.

CORRECTIVE ACTION: NONE X (CHECK ONE) REQUIRED CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
Failed VCE	Positive saturation of V.A. or negative saturation of integ triggers BTV, giving BGG signal and driving the sustainer full-on.	None.	TM records show no saturation, no BGG, and a sustainer full-on signal; VCE checked OK on G&C SAIE and test console.	None.

CORRECTIVE ACTION: NONE X (CHECK ONE) REQUIRED

CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION

CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
TVC Coil.	TVC short causes power battery drain at first pulse, causing voltage drop on power battery end resulting transient fires BTV.	None.	Post-test resistance checks showed 37 ohms which is within spec.	None.

CORRECTIVE ACTION: NONE X REQUIRED (CHECK ONE)

CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION

CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
Engine, external, G&C harness short.	Short in harnesses leading to TVC valve causes power battery drain at first pulse	None.	TM records show normal inductive kick at TVC turn-off indicating no short.	None.

CORRECTIVE ACTION: NONE X (CHECK ONE) REQUIRED

CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
Shorted diode in MTS.	Shorted diode in MTS causes power battery drain when MTS power was shut down.	None.	Post-test checkout of MTS and diode showed normal operation.	None.

CORRECTIVE ACTION: NONE X REQUIRED (CHECK ONE) CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION

CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
PSE short.	Short in PSE causes power battery drain which caused the transient triggering the BTV.	None.	Post-test functional checkout of G&C pkg showed PSE functioning properly.	None.

CORRECTIVE ACTION: NONE X (CHECK ONE) REQUIRED

CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION

CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
Pad wiring.	Pad wiring short in MTS monitoring circuitry causes power battery drain.	None.	Post-test pad check-out showed all pad wiring functioning properly; there is no connection between time delay mod power and launch sequence power.	None.

CORRECTIVE ACTION: NONE X (CHECK ONE) REQUIRED

CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION

CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
Pad wiring.	Pad wiring short in MTS monitoring circuitry causes power battery drain.	None .	Post-test pad checkout showed all pad wiring functioning properly; there is no connection between time delay mod power and launch sequence power.	None.

CORRECTIVE ACTION: NONE X (CHECK ONE) REQUIRED

CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION

CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
XM811 Timer.	Premature signal from XM811 timer firing the SECO circuit triggering the BTV.	SECO timer squibs were found to have been fired.	TM records show valve amp commanding full-on sustainer and films show sustainer full-on; TM record shows no BGG signal; pins pulled from G&C test connector at impact can short BGG monitor PT to ground which will initiate timer.	None.

CORRECTIVE ACTION: NONE X REQUIRED (CHECK ONE)

CONCLUSION: Not cause, timer was most likely initiated at impact.

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION CAUSE PROBABILITY ESTIMATE: POSSIBLE

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
Instrumentation.	Instru. short causes saturation on integ or V.A. or causes power battery drain.	None.	TM records all show normal functioning with no evidence of short; all TM monitoring points are current limited.	B/H checkout at LTV AC-M.

CORRECTIVE ACTION: NONE X (CHECK ONE) REQUIRED

CONCLUSION: NOT CAUSE

TABLE A-1. (Continued)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION:: BECO AT ENGINE IGNITION   CAUSE PROBABILITY ESTIMATE: UNLIKELY

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
External impedance.	Large external impedance at power connector causes voltage drop at TVC pulse.	Evidence of poor crimping based on X-ray.	Calculations of voltage drops for the varying loads shows impedance reduction with time which is not indicative of fixed external impedance; post-fit dissection of battery showed no crimp anomaly; battery voltage recovered to 30.4 V with G&C load.	None.

CORRECTIVE ACTION: NONE X (CHECK ONE) REQUIRED   CONCLUSION: NOT CAUSE

TABLE A-1. (Concluded)

ROOT CAUSE ANALYSIS CHART

FAILURE INDICATION: BECO AT ENGINE IGNITION CAUSE PROBABILITY ESTIMATE: PROBABLE

SPECULATION		EVALUATION		
FAILURE MODE	FAILURE SEQUENCE	SUPPORTING DATA	REFUTING DATA	ADD'L DATA TESTS REQ'D
Battery internal impedance	Large internal impedance at time of first TVC pulse lowers battery voltage, causing MTS shut down which results in loss of PSE regulation introducing transient of -22 which fires the one shot, triggering the BTV.	Test using 29 ohm load in series with power battery (high internal impedance simulations) reproduces flight failure and comparison of test TM records with flight records shows duplication of all flight records.	None.	None.

CORRECTIVE ACTION: NONE CONCLUSION: ROOT CAUSE

(CHECK ONE)

REQUIRES X power transistor redesign

failure sequence. Table A-2 presents a summary of all flight tests in which TVC pulsing occurred prior to the time at which the missile clears the rails. The pertinent flight's time sequences are illustrated in Figure A-5.

As indicated from these data, four recent instrumented flights were noted to have had TVC pulses prior to First Motion. These were Flights 151, 153, 155, and 156. The time sequence of these four and Flight 162 along with the power battery effects are as follows:

Flight	Power Transfer	Gyro Sensitivity	First TVC Pulse	Power Transfer Pulse	First Motion	Power Battery Results	Remarks
151	1.223	1.313	1.292	1.295	1.539	No noted drop	Full 13 msec duration pulse on power transmitter channel prior to SPGG
153	1.374	1.460	1.645	1.658	1.920	Drop to 24 V	MP off prior to first motion
155	1.336	1.437	1.632	1.636	2.139	No noted drop	Small 2 msec spike on power transmitter channel.
156	1.442	1.533	1.962	None	2.036	No noted drop	No apparent effect
162	1.464	1.537	1.535	1.548	1.797	Drop to 14 V	MTS cff and BECO prior to first motion.

4.2 TVC Pulsing During Launch Sequence

As indicated in the previous subsection, 10 out of 36 flights investigated showed TVC action prior to first motion. Potential reasons for this early TVC pulsing are large gyro uncage errors and capacitive loading of the PRM nulling amplifiers. To evaluate the latter, measurements were made at WSMR to determine the capcitive load presented by the pad wiring. Concurrently, tests were conducted in the simulator to determine the effects of capacitance on the DCE-M/P null loop. WSMR measurements showed that the capacitive load presented by the pad wiring and hardwire van at the DCE-M/P null loop monitoring points to be 0.01 μf. Simulator tests showed that capacitive loading up to 1 μf had no effect on the null loop.

TABLE A-2. LANCE SUMMARY OF FLIGHT TEST TVC ACTION

Flight No.	Power Battery S/N	Power Battery Lot	Gyro S/N	TVC Action Power Transfer F.M.	TVC Action F.M. End Rails
72	44	(02)			X
76	125	(04)		X	X
84	149	(03)		X	X
90	176	(04)			
105	180	(04)	(64A)		X
107	107	(04)	(2001)		X
110	202A	-	(47B)	X	X
111	66	(02)	(2017)	X	X
112	198A	-	(2008)	X	X
116	1186	(2)	(2202)		X
119	1185	(2)	(2210)		X
121	EP6	(1A)	(2018)		X
127	1194	(2)	(2216)		X
130	1191	(2)	(2207)		X
131	1122	(1A)	(2249)		X
132	1104	(1A)	(2294)		X
133	1121	(1A)	(2238)		X
135	1181	(2)	(2218)		X
137	1147	(1A)	(2226)		
142	1184	(2)	(2205)		
145	1159	(1A)	(2231)		
147	1152	(1A)	(2293)		X
148	1145	(1A)	(2229)*		X
149	1139	(1A)	(2244)		X
150	1155	(1A)	(2248)		X
151	1187	(2)	(2206)	X	X
152	1174	(2)	(2222)	X	X
153	1116	(1A)	(2230)	X	X
154	1192	(2)	(2215)		X
155	1105	(1A)	(2223)	X	X
156	1114	(1A)	(2234)	X	X
157	1168	(1A)	(2251)		X
158	1161	(1A)	(2284)		X
159	1126	(1A)	(2252)		X
161	1177	(2)	(2278)		X
162	1227	(3)	(2286)	X	X

*Denote hardwire records not available.

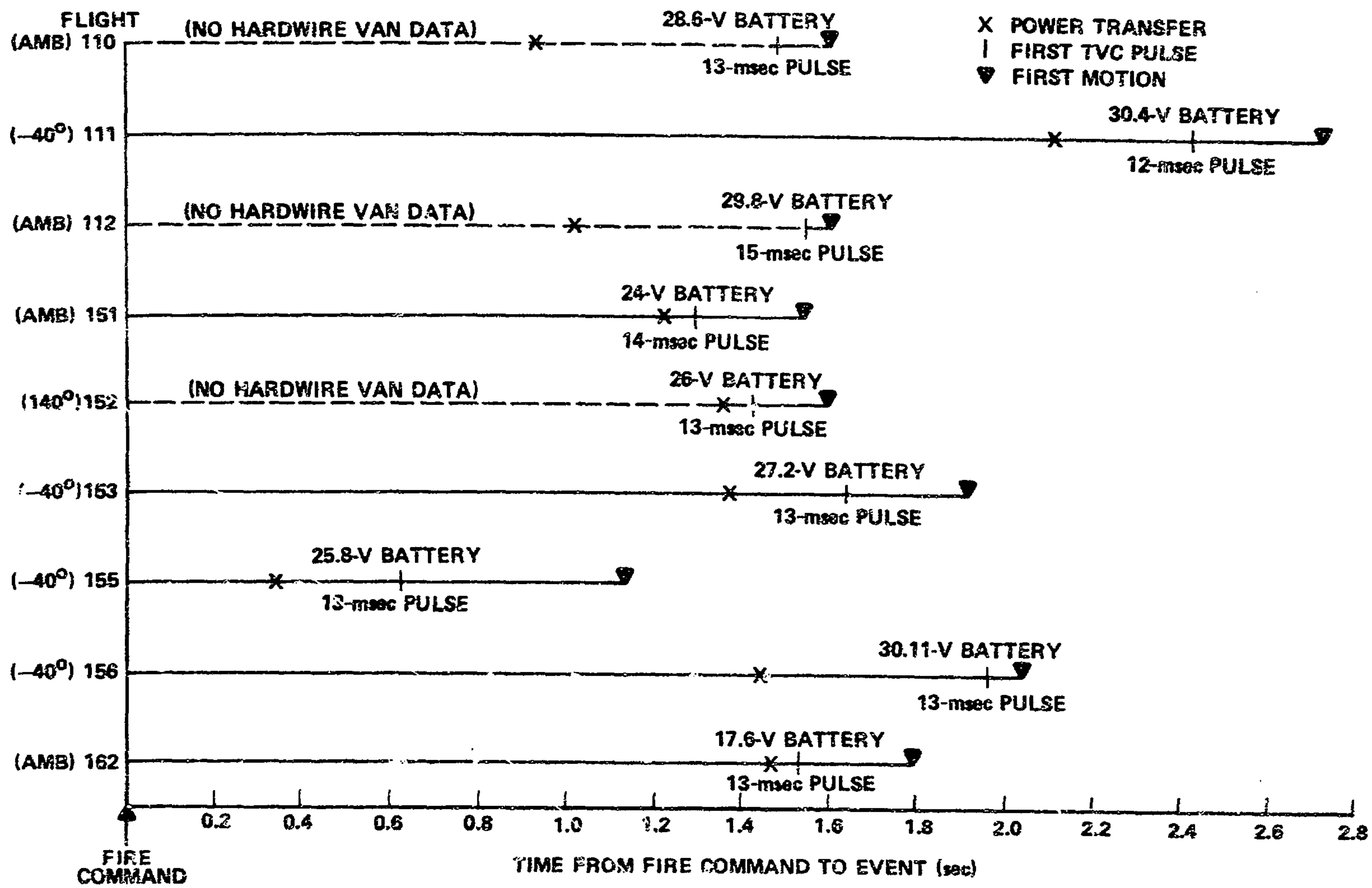


Figure A-5. Time sequence – previous flights.

The effects of a gyro uncage kick on the closed nulling loop was then evaluated. In the simulator, a step function simulating uncage was introduced into the null loop. The results are tabulated below.

Gyro Output	TVC Pulsing
37 mV	No pulsing
38 mV	1 pulse
52 mV	2 pulses

As shown above, a step input of less than 37 mV will not cause any pulsing. Between 38 and 51 mV, however, the response of the null loop is such that one TVC pulse will be generated before the loop settles at a new null point. With a 52 mV step input, two pulses will be generated before the loop settles down.

Since this flight was a piggyback gyro flight, the Δ error signals between the control gyro and the piggyback gyros allowed a precise determination of the uncage kick.

The magnitudes are as follows:

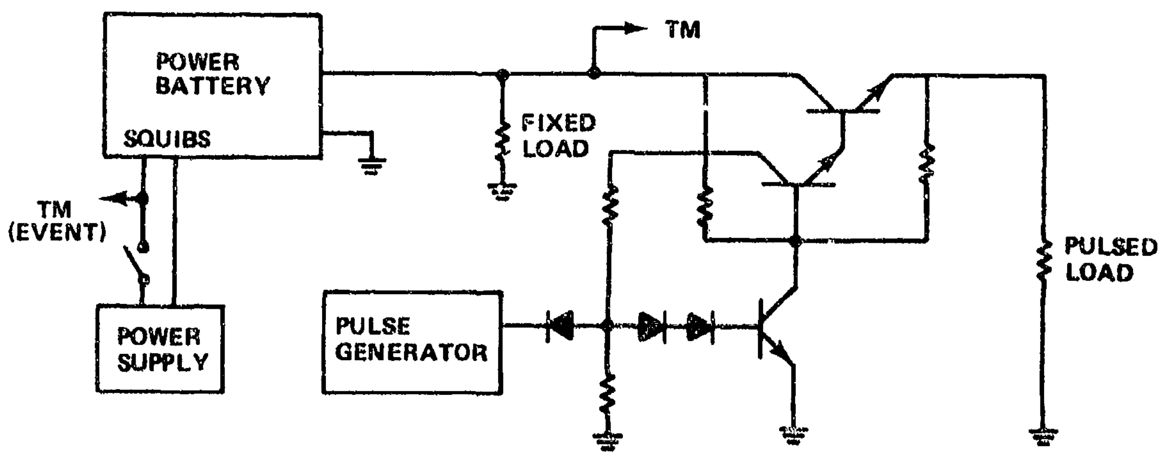
$$\text{Pitch} = 3.5 \text{ min} = 29 \text{ mV}$$

$$\text{Yaw} = 5.5 \text{ min} = 46 \text{ mV} \quad .$$

From these data, it can be seen that the early TVC pulse on this flight was definitely the result of a gyro uncage error.

4.3 Power Battery Internal Impedance

The time history of the power battery internal impedance was evaluated by applying a pulsed load. The voltage drop which occurs upon application of the load results in two equations with two unknowns: open circuit voltage and output impedance. The test circuit is illustrated as follows:



At initiation, the internal impedance is at infinity. As the electrolyte melts and current flow starts, the internal impedance rapidly decreases toward values less than 1 ohm. Figures A-6 and A-7 show the time history of output impedance for two test samples starting at the point where the open circuit (unloaded) voltage reaches 28 Vdc. Note that both batteries reached 28 Vdc at about 1-1/2 seconds after initiation of the battery squibs. The output impedance at this point in time is approximately 12 ohms. The application of a 14-ohm load (equivalent to 2 TVC valves) at this time will cause the battery voltage to drop nearly in half. The slope of the impedance curve is very steep (75 ohm/sec) and the battery voltage under load will recover back to 26 Vdc in approximately 200 msec.

The internal impedance of the power battery used on this flight can be calculated from flight data and hardwire records as shown in Figure A-8. The TVC supply provides a continuous record of battery voltage even during TVC pulsing. By accounting for the voltage divisions within the TM package during pulsing and utilizing both the pitch and yaw TVC channels, the power battery voltage can be reconstructed as shown. Knowing the load of each TVC valve and recognizing that the battery supplies the entire G&C package following MTS shutdown, the battery load profile can be reconstructed. The determination of output impedance is now a simple calculation and a time history of the battery output impedance during the time frame of interest is also included in Figure A-8. It will be noted that the output impedance of the flight battery well after the point where the output reaches 28 V is 24 ohms which is significantly higher than the batteries tested.

4.4 Battery Lot Data

Because of the significant difference between the flight battery and the batteries evaluated in the lab, the characteristics of various battery lots were evaluated. The lot information is as follows:

Lot No.	S/N	Sample Test Date
1A	1101 - 1172	12/70
2A	2273 - 1194	1/71
3	1195 - 1268	5/71
4	In-process	6/72

The lot sample tests call for the application of 13 ohms when the unloaded voltage reaches 28.5. Time for the loaded output to recover back to 26 V is recorded. The lot sample data are summarized in Table A-3. The upper figure in each case is the mean while the lower figure is the standard deviation.

It will be noted that Lot 3 data show significantly larger voltage drops upon application of the load than the previous lots. This is indicative of higher output impedance values. This flight

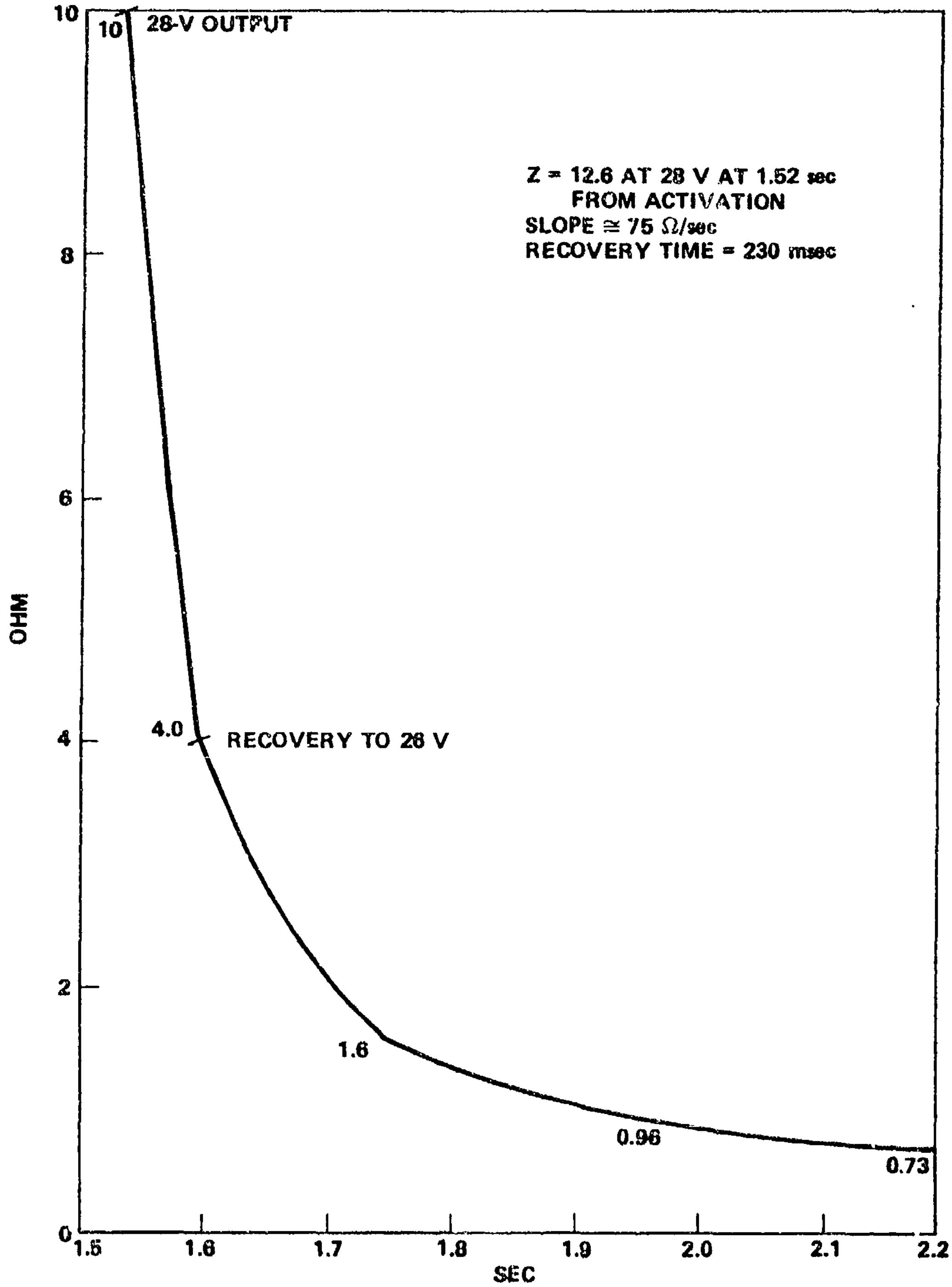


Figure A-6. Number 1 — 2a pulse and 14-ohm load.

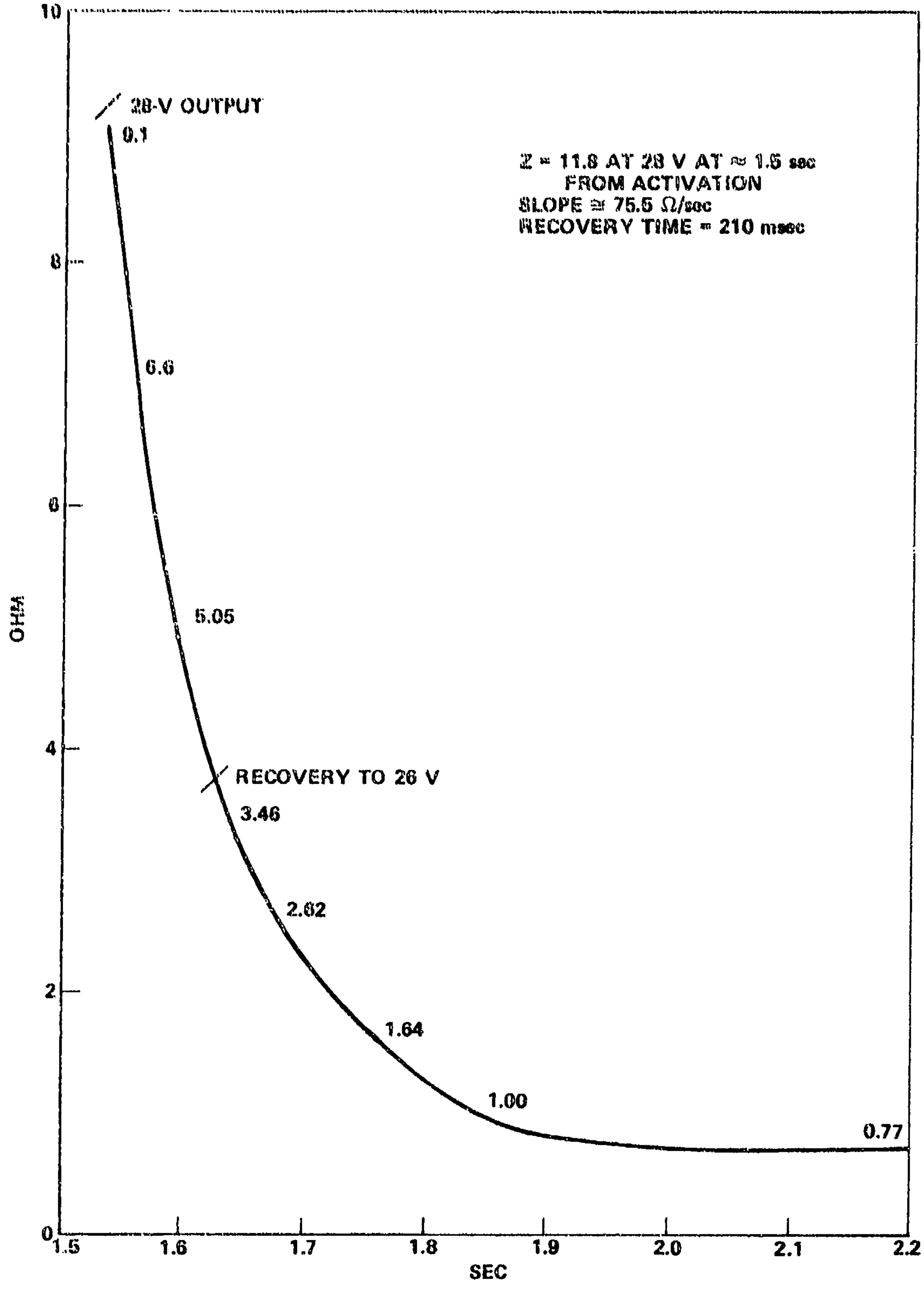


Figure A-7. Number 2–2a pulse and 14-ohm load.

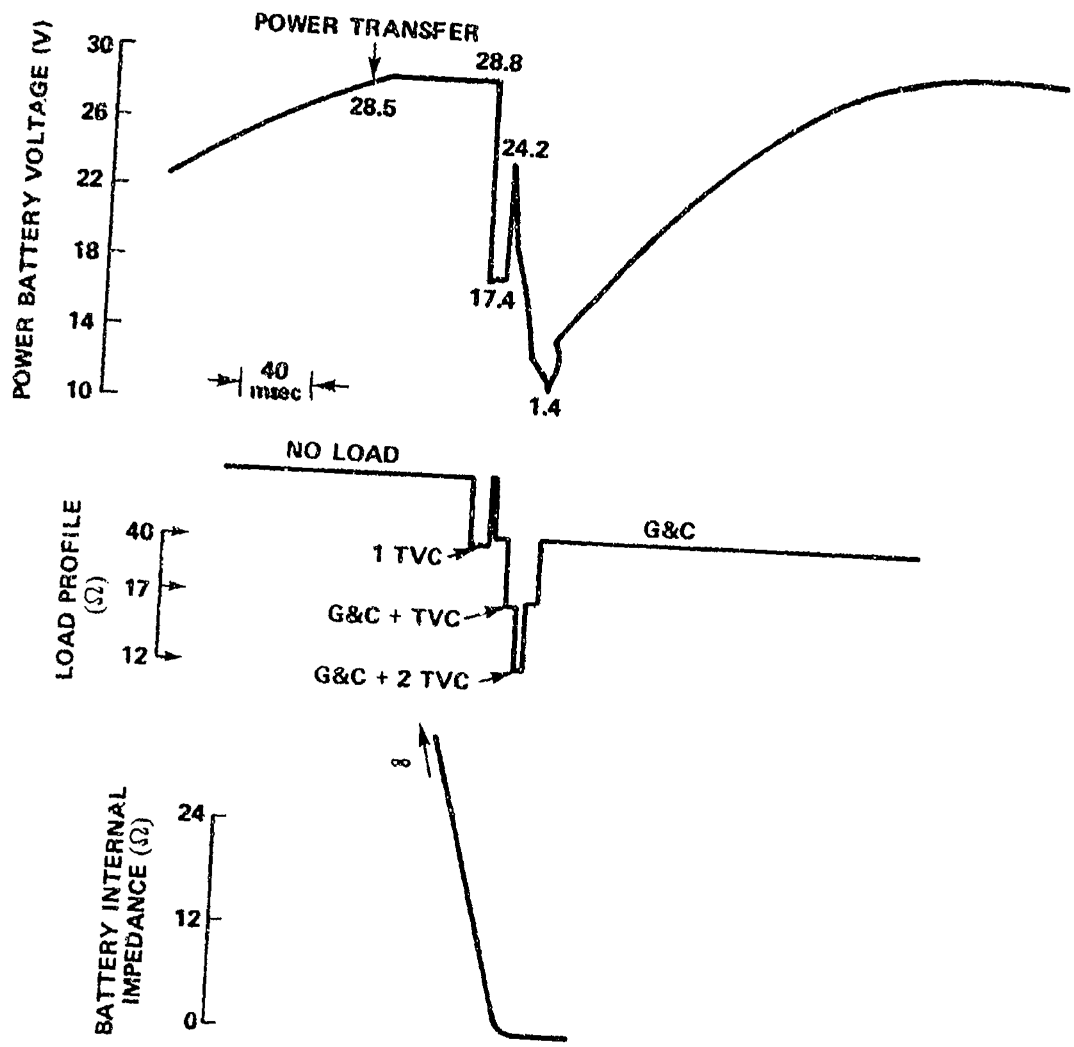


Figure A-8. Flight 162 power battery internal impedance.

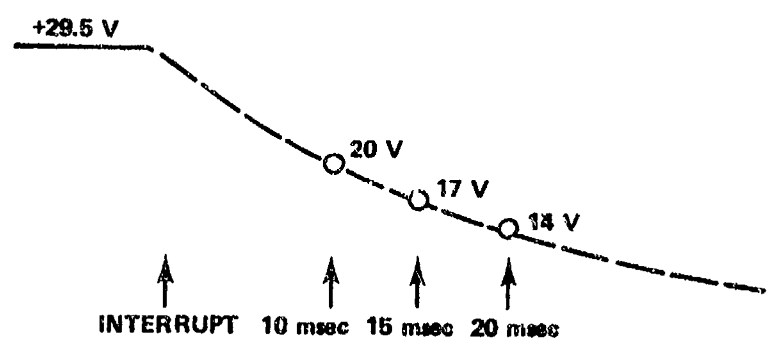
TABLE A-3. LANCE BATTERY LOT SAMPLE DATA 13-OHM LOAD APPLICATICN

Lot	Temperature (°F)	Time to 28.5 volts	Voltage at Load Application	Time to Recover 26.0 volts	No Battery Tested
1	+200	0.94 / 0.029	10.30 / 1.947	0.13 / 0.03	(10)
	-40	1.52 / 0.088	4.5 / 2.06	0.50 / 0.126	(5)
1A	+200	1.018 / 0.058	14.44 / 1.395	0.11 / 0.02	(5)
	-40	1.36 / 0.103	6.75 / 1.34	0.33 / 0.055	(4)
2A	+200	1.01 / 0.03	14.63 / 1.026	0.15 / 0	(3)
	-40	1.43 / 0.35	5.57 / 1.87	0.35 / 0.07	(2)
3	+200	1.1 / 0.055	5.0 / 1.70	0.20 / 0.02	(5)
	-40	1.86 / 0.070	3.7 / 0.80	0.46 / 0.048	(5)
4	+200	1.17 / 0.039	8.14 / 3.61	0.197 / 0.064	(5)
	-40	2.00 / 0.079	9.30 / 2.54	0.408 / 0.051	(5)
5	+200	1.31 / 0.020	27.88 / 0.66	- / -	
	-40	2.41 / 0.046	26.03 / 0.45	- / -	

utilized power battery S/N 1227. This was the first battery flown out of Lot 3. Thus, the lot sample data confirms the reconstructed output impedance of the flight battery. Further evidence of the significant differences between this first of the Lot 3 batteries and all previously flown batteries can be seen in Figure A-9 which shows the effect of TVC pulsing prior to first motion on the power battery voltage.

4.5 Simulated Power Transient Tests

Results to this point have shown that the Lot 3 power batteries (the first of which was flown on this round) exhibit a significantly higher output impedance following attainment of open circuit voltage sufficient to allow the power transfer event. Also, gyro uncage kicks can upset the DCE-M/P null loop and cause TVC pulsing prior to first motion which presents a load to the power battery during this period of high internal impedance. The effects of such a power transient upon the G&C system were examined in the simulator. The initial test set-up is shown in Figure A-10. The results of the initial power interrupt tests are as follows:



As noted, the power battery voltage follows a discharge curve due to the distributive capacitance of the G&C package. The longer interrupt times resulted in lower voltages. The telemetry records of the G&C measurements during the power interrupt showed a close match to flight records when the interrupt time was greater than 10 msec. Similar results were obtained with various combinations of three VCE's and three PSE's, indicating that the effects of the interrupt were not a function of individual VCE's or PSE's.

To provide a closer simulation to Flight 162, a 29 ohm load was inserted in series with the power battery simulating a high output impedance. Figure A-11 shows the data as recorded by TM. Comparison of this record with the actual flight records (Figure A-1) shows that this simulation matches all flight characteristics:

Premature BECO

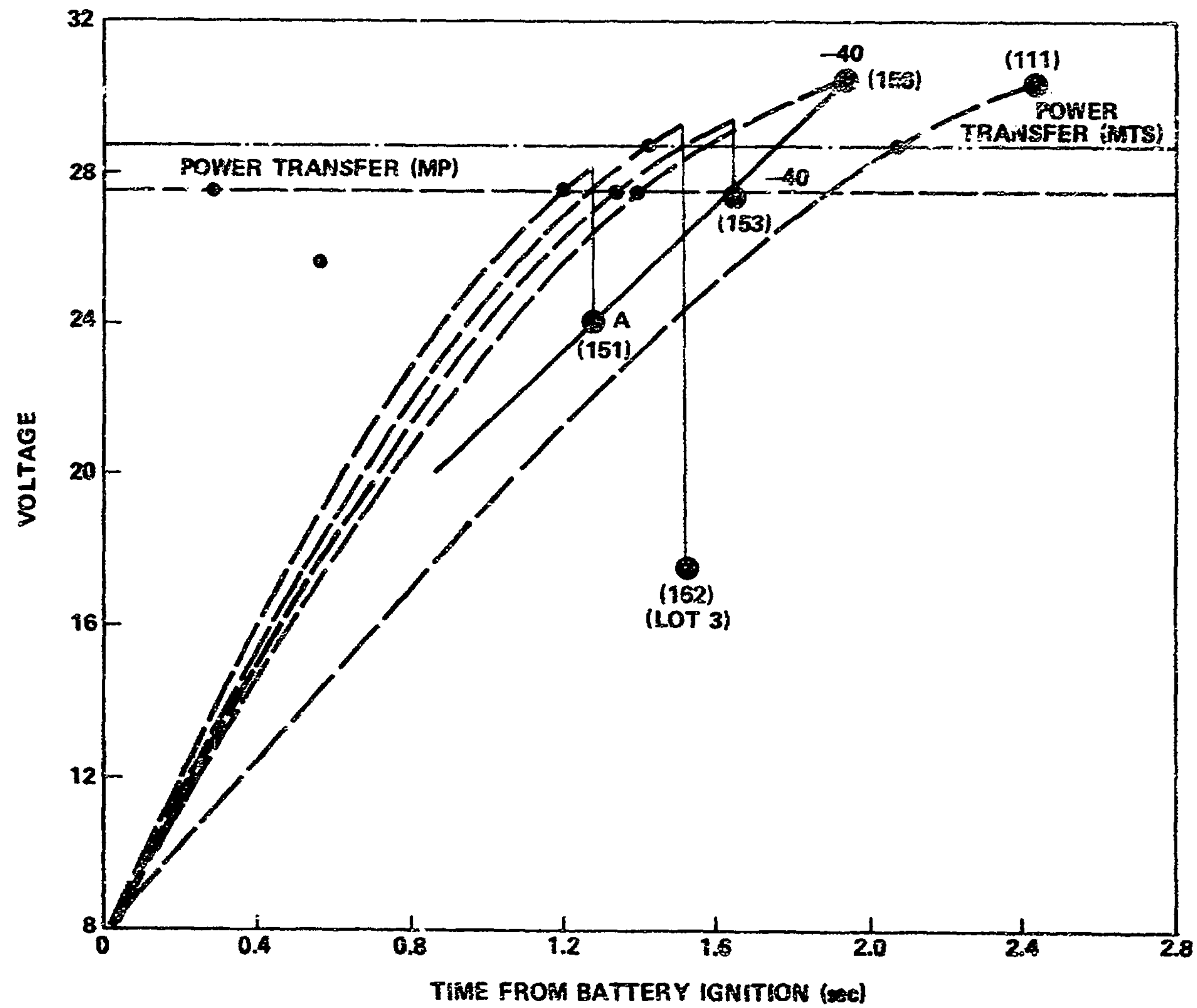
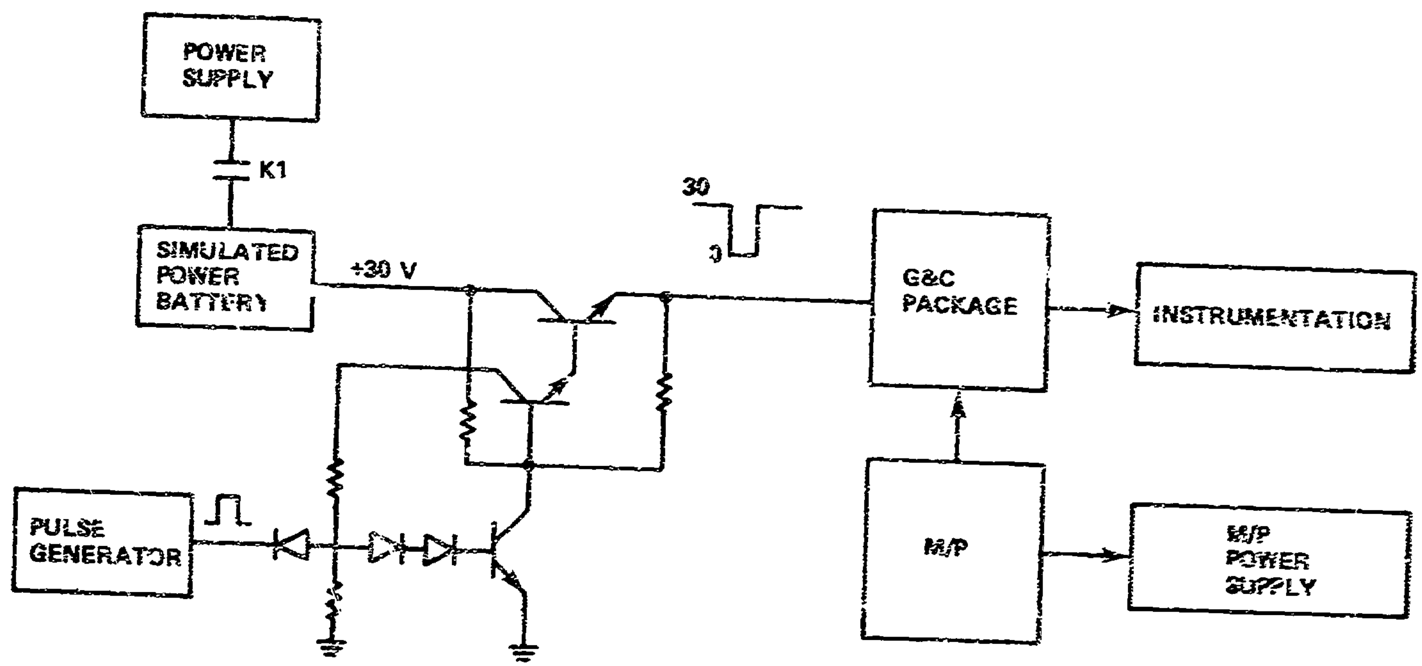


Figure A-9. LANCE power battery voltage drop flight results.



- K1 RELAY CLOSES AT FIRE COMMAND SIMULATING POWER BATTERY RISE
- LAUNCH SEQUENCE IS HALTED BETWEEN SPGG AND FIRST MOTION
- POWER INTERRUPT INTRODUCES ELECTRICAL TRANSIENTS TO THE G&C WHICH IS MONITORED BY INSTRUMENTATION SYSTEM IV

Figure A-10. Power interrupt test setup.

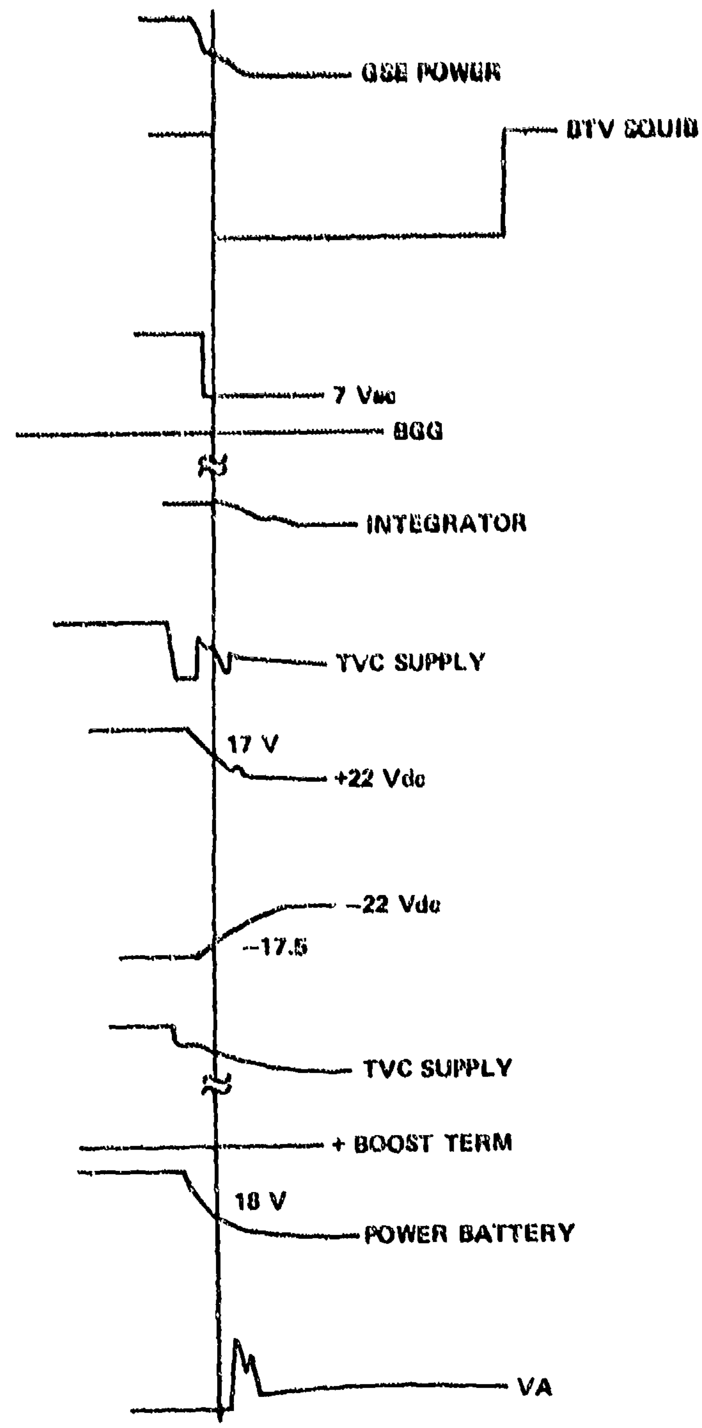
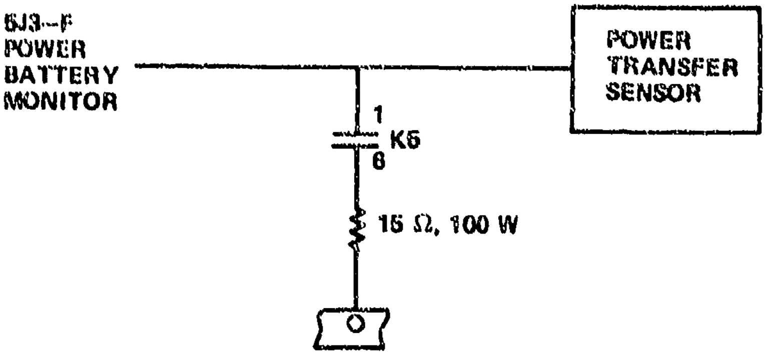


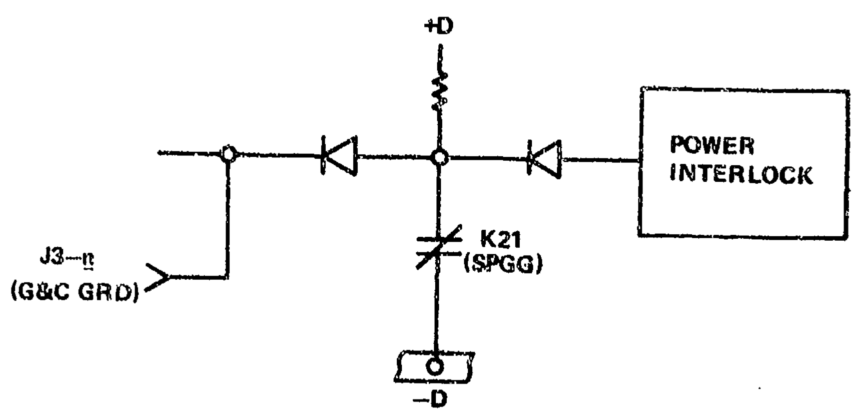
Figure A-11. Run number 33 flight package 29 - ohm load in series with power battery simulator.

The optimum method of accomplishing this objective was a modification to the M/P power transfer function to incorporate a 15-ohm load as follows:



Since the power transfer sensor is set for 27.5 V, this modification ensures that power transfer will not occur until the power battery is capable of supplying two amperes minimum.

In addition to initiating the power battery under load, the flight results also show that a more positive indication of umbilical disconnect should be incorporated into the M/P. This was accomplished by changing the power interlock input from the power transfer sensor output to the G&C ground as follows:



These two changes were incorporated prior to Flight 163.

Boost good guidance inhibited
MTS shutdown
All electrical transients similar to flight.

5.0 CONCLUSIONS AND CORRECTIVE ACTION

5.1 Conclusions

Examination of previous flight records shows that TVC pulsing prior to first motion can be expected. These pulses are dependent on the magnitude of the gyro uncage error. Simulator tests have shown that the response of the DCE-M/P null loop is such that one TVC pulse will be generated before the loop settles to a new null when the uncage kick lies in the range of 38 to 52 mV. The special piggyback gyro telemetry on this round verified an uncage error in the yaw plane of 46 mV.

This flight was the first to use a Lot 3 power battery. Comparison of the battery lot sample data shows that Lot 3 exhibits significantly higher internal impedance at the point where the power transfer event occurs in the launch sequence than all previously flown lots. Initiation of the gyro, its subsequent uncaging error, and the resulting TVC pulsing presents a load to the power battery during this period of high internal impedance, reducing its output voltage to the point where the MTS "senses" umbilical disconnect and causes MTS power shutdown. This action causes the G&C package itself to act as an additional load on the power battery, further reducing its output voltage to the point where the PSE loses regulation, causing the PSE +22 Vdc supply to drop. The -22 Vdc supply which is derived from the +22 Vdc exhibits a positive-going transient toward zero. This positive spike couples through the VCE one-shot timing capacitor to trigger the one shot for 60 msec which fires the BTV squibs through the power switch.

Simulator tests using a 29-ohm load in series with the power battery to simulate the high internal impedance reproduces the flight failure and comparison of the resulting TM records with flight records duplicates all flight characteristics:

Premature BECO
Boost good guidance inhibited
MTS shutdown
All electrical transients similar to flight.

5.2 Corrective Action

Battery lot sample data as well as the results of Flight 162 indicate that the ability of the power battery to handle early loading is marginal. To ensure that the power battery internal impedance is sufficiently low so as to ensure the loading capability, the power battery should be initiated and allowed to come up to voltage under a load.

Appendix B. INFORMATION SOURCES CONTENTS

1. Government-Industry Data Exchange Program

Abstracts of technical reports are distributed under the Government Industry Data Exchange Program (GIDEP). GIDEP is a cooperative interagency activity whose task is to provide automatic interchange of test data on parts/materials among Government contractors and agencies, thereby improving the reliability and performance of such parts/materials.

These abstracts have been prepared to facilitate research in available sources of data, to assist in the selection of parts and materials, and to provide awareness of new state-of-the-art information in specialized fields.

These reports are usually available in microfilm form. For further information concerning GIDEP, contact the document section of your technical library.

A sampling of alert services provided under this program are as follows:

Processing, Heat Treating D6ac Steel
Lindberg Heat Treating Co.
570.40-EO-A-73-02* (E2398).**

> Tensile bars for longerons failed during test by an independent test laboratory. Preliminary investigation indicated that the most probable cause of the carburization was due to inadequate control of the atmosphere during the heat treat cycle (1 page).

Relay, High Voltage, High Sensitivity, Reed Type.
An Application ALERT
601.14-J4-A-73-01 (E2399).

> Exposes an application anomaly experienced during ground testing of a relay switched high voltage solar array power supply. Repetitive relay contact closures occurred under unenergized relay coil conditions. This was attributed to electrostatic force attraction of the reeds due to a dc potential of 1200 volts across the relay contacts augmented by reed motion precipitated by mild spacecraft motion (1 page).

NOTE: Normally, the GIDEP report number and the access number will be required to order a report

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*GIDEP report number.

**Access number on microfilm.

Summary of GIDEP Reports
Cartridge No. E-12
Access Numbers E2397-E2586

General Reports

Development of Low Temperature Curing Structural Adhesives (Dec. 72), 085.45.40.30-EO-01 (E2432).
Discusses an effort to increase toughness of epoxy based adhesives without sacrificing thermal stability by modifying the adhesives with flexibilizers, and describes development of room temperature curing silicone adhesives having extremely lo low modulus and density. The properties of these silicone adhesives are presented (24 pages).

Printed Circuit Card Temperature Test (Sep. 73), 142.40.13.17-EC-01 (E2435).
Presents test methods and results of testing conducted to determine the effects of over-temperature conditions on printed wiring assemblies. Various sample lots were tested at temperatures of 400° and 500°F with exposure times ranging from 1 minute to 7.5 minutes. All samples then were subjected to moisture resistance cycles per MIL-STD-202. Insulation resistance measurements were made after each of the two above tests (5 pages).

Urgent Data Request Response Report (Jun 73), 153.36.00-Y3-03 (E2445).
Summarizes responses received to an Urgent Data Request concerning leakage and shorting failures which had been occurring on the CL 65 type wet tantalum capacitor (1 page).

Chemical Vapor Deposition of Dielectric Thin Film (Dec. 72), 331.33.33.50-EO-01 (E2456).
Describes chemical vapor deposition (CVD) in general and presents the various methods for depositing dielectric thin films by CVD. The report includes a discussion on the uses, deposition parameters, and properties of low-temperature silicon dioxide, high temperature silicone dioxide, and silicon nitride (52 pages).

Infrared Spectral Emmittance of Five Black Coatings (Jun. 70), 331.40.00.00-X7-01 (E2459).*
Reports on the results of measurements and studies made on five black coatings. Three of the coatings were available under the commercial names of Sicon Black, 3M Velvet Coating, and Cat-a-Lac Flat Black. The two remaining samples were a platinum black chemically deposited on a gold film and a platinum black suspended in an epoxy.

*Report was not microfilmed because of distribution limitations.

2. National Technical Information Service Reports

Abstracts of technical reports produced under Government funded research and development projects are published by the National Technical Information Service (NTIS) as a "current awareness" service. These reports cover unclassified Government sponsored research in physical sciences, engineering, and related technology.

The abstracts can be used by scientists and engineers to survey current activity in the area of their professional interest and choose publications believed to be valuable for their work.

The document section of the technical library usually has some of these reports in microfiche form, other may be ordered as required. A sampling of abstracts ·· ovided under this program are as follows:

a. Tooling, Machinery, and Tools

-Highlight-
Hydraulic Grip System for Composite Tube Specimens.
A. Nagy, and U.S. Lindholm.
Southwest Research Inst., San Antonio, Tex., Sep. 73, 35 p.
AFML-TR-73-239
AD-770 447/1WI   PC$3.00 MF$1.45

The report describes the development of a hydraulic grip system for use in the mechanical testing of composite tubular specimens under biaxial loads. The objective of the grip system is to eliminate the constraints imposed by rigidly bonded end tabs which generally lead to premature failure in strength tests. The new hydraulic grip uses a uniform clampint pressure to transfer axial and torsional loads to the specimen and an active, servo-controlled, differential clamping pressure to produce radial displacement in the grip which compensates for changes in diameter of the specimen gage section during loading. This active control feature minimizes the bending stresses at the specimen-grip interface. Preliminary tests with the grip demonstrate its load transfer capability and the active compensation feature. (Author)

b. Manufacturing Processes and Materials Handling

Cam Path Drawing, an Automatic Drafting Machine Application.
V. H. Montuori.
Watervliet Arsenal, N. Y., Nov. 73, 13 p., M-WV-T-3-47-73
AD-770 368/9WI   PC$3.00/MF$1.45

The report is on a practical and simple application of an automatic drafting machine. Cam paths normally drawn by hand are now computerized and drawn in less than two hours. A FORTRAN program has been written to cover all types of cam paths drawings. (Author)

-Highlight-
Casting Technology Relevant to the Production of High Strength Aluminum Sand Castings.
Alan G. Fleming and G. B. Singh.
Army Tank-Automotive Command, Warren, Mich., Nov. 73, 29 p., TACOM-TR-11727
AD-770 501/5WI PC$3.00/MF$1.45

High-strength aluminum sand casting alloys such as type 201 and 224 offer yield strengths upwards of 55,000 psi on bars cut from castings. The range of properties represented expands the technical base and design strength range of aluminum castings; their utilization will result in longer service life as a consequence of improved heat rejection capability and lowered running temperatures under high ambient temperature operation. Significant weight savings realized in individual applications should enhance vehicle mobility characteristics. (Author)

3. National Aeronautics and Space Administration, Quality Assurance Briefs

Abstracts and reports related to parts reliability, failure analysis reports, quality assurance survey reports, and general quality data are prepared by Goddard Space Flight Center and, as a courtesy, copies are made available to other Government agencies.and contractors. These advisory reports may be requested through the contracting officer to the Chief, Quality Assurance Branch, Parts Branch, Code 311, Goddard Space Flight Center, Greenbelt, Maryland 20771.

4. Sample of Titles from the Engineering Index (1969)*

Design Effective Failure Mode and Effect Analysis, P. L. Crown, Proc. Annual Symposium on Reliability, Chicago, Ill., Jan. 21-23, 1969, IEEE, New York, Vol. 2, No. 1, 1969, p. 514-21, 20134**

Mechanical Failure Technology — Coordinated Government Program, M. B. Peterson and D. Flage, Proc. Annual Symposium on Reliability, Chicago, Ill., Jan 21-23, 1969, IEEE, New York, Vol. 2, No. 1, 1969, p. 127-32.

---

*Published by Engineering Index Inc., 345 East 47 Street, New York, New York, monthly and annually.

**Abstract or item number.

Effectivenss of Part Pre-failure Analysis; R. C. Aakhus (Honeywell, Inc., Hopkins, Minn.), H. W. Luedtke, IEEE Proc. Annu. Symp. Rel., Low Angeles, Calif., Vol. 3, No. 1, Feb. 3-5, 1970, p. 267-72.

Documenting and Evaluation Troubles in Military Systems; T. L. Tanner (Bell Telephone Labs., Inc., Whippany, New Jersey); Am. Soc. Quality Control - Annual Tech. Conference, 23rd - Trans, May 5-7, 1969, Los Angeles, Calif., p. 33-43.

Useful Test Design for Physics of Failure Investigations; R. N. Miller (TRW Systems, Redondo Beach, Calif.); Amer. Soc. Quality Contr., 11th annual West Coast Reliability Symp., Los Angeles, Calif., May 15, 1970, p. 133-57.

Microelectronic Failure Analysis Techniques and Application; E. A. Doyle, Jr. (Rome Air Development Center, Griffiss Air Force Base, New York), G. G. Sweet and A. M. Marques; Rochester Soc. Quality Contr, 26th Conf. Trans., 1970, p. 43-5.

Reliability - What Happens If, E. F. Taylor, Proc. Annual Symposium on Reliability, Chicago, Ill., Jan 21-23, 1969, IEEE, New York, Vol. 2, No. 1, 1969, p. 62-7.

Fault Tree and Reliability Analysis Comparison, K. H. Eagle, Proc. Annual Symposium on Reliability, Chicago, Ill., Jan 21-23, 1969, IEEE, New York, Vol. 2, No. 1, 1969, p. 12-17.

Failure Mode, Effects, and Criticality Analysis, K. Greene and T. J. Cunningham, Proc. 1968, Annu. Symp. Reliability, Jan. 16-18, 1968, IEEE, 1968, p. 374-84.

Failure Data Feedback - Contributions of Reliability Analysis Center, G. T. Jacobi and H. A. Lauffenburger, 7th Annual Reliability Physics Symposium, Washington, D. C., Dec. 2-4, 1968, IEEE, New York, Session V, Paper 1, p. 42-3.

5. Scientific and Technical Analysis Centers

Root cause diagnostic studies often require technical reference materials and/or the services of technical specialists to support the diagnostics activities. Finding relevant reference material or individuals with the skills required is often difficult. The services of Scientific and Technical Information (STINFO) Analysis Centers can speed up the process and provide individuals with backgrounds related to diagnostic activities.

A STINFO analysis center is an organization exclusively concerned with review or analysis of scientific or engineering data and whose functions are concerned primarily with handling the technical information in the documents rather than distribution of documents.

The STINFO program disseminates technical data and documents or their abstracts and disseminates by all other means information that is the product of or in direct support of RDTE and related processes and the management thereof through the phase of design release to production.

Advantage should be taken of individual user services offered by centers. Replies to questions can consist of specific items of evaluated data or information, current summaries on technical trends, comprehensive state-of-the-art analyses, and specialized advisory services.

Scientists and engineers may communicate directly with STINFO analysis centers for other than documented information.

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1 September 1972

F O R E W O R D

This revised directory of the Defense Documentation Center (DDC) Referral Data Bank, (previously issued in October 1970 as AD-712 800 and in July 1971 as AD-724 700) lists specialized scientific and technical sources of information which have the capability of service to the defense community, supplementary to the documentation services of DDC. The information sources, operated or supported by the Department of Defense and other Federal Government agencies, include information analysis centers and other information centers, data centers, information offices and libraries, laboratories and testing directorates, information exchanges, audiovisual depositories, etc. The Department of Defense information analysis centers are identified by an asterisk in both the table of contents and activity index.

The directory consists of a compilation of computer printouts, each of which gives for a single activity detailed descriptive information on the mission, subject areas, services and materials available, publications issued and access limitations. The descriptor field on the printout is limited to five lines because of space limitations, although additional terms are stored in the data bank for retrieval purposes. Arrangement of printouts is by referral accession number. Missing numbers represent activities which have been merged, deactivated and/or deleted. Three indexes, by activity, subject areas and director/contact, refer to the appropriate accession number and facilitate use of the directory.

To obtain further information regarding any STINFO facility, write or call the director or information specialist at the address and telephone number given.

Users of this directory are requested to report to DDC any omissions and errors of fact, as well as suggestions for improvement of future issues. Comments should be sent to the Defense Documentation Center, ATTN: DDC-TSR-2, Cameron Station, Building 5, Alexandria, Va. 22314.

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TABLE OF CONTENTS

*Department of Defense Information Analysis Center

*Department of Defense Information Analysis Center

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Appendix C. SUGGESTED REFERENCE READING LIST

1. Simon, Herbert A., The New Science of Management Decision, Harper and Row, New York, New York, 1960.

2. Blake, Robert R. and Mouton, Jane S., The Managerial Grid, Gulf Publishing Company, Houston, Texas, 1964.

3. Maier, Norman, F., Problem-Solving Discussions and Conferences, McGraw-Hill Book Company, New York, New York, 1963.

4. Osborn, Alex F., Applied Imagination, Scribner, New York, New York, 1953.

5. Drucker, Peter F., Managing for Results, Harper and Row, New York, New York, 1964.

6. Jones, Manley H., Executive Decision Making, Richard D. Irwin, Homewood, Illinois, 1957.

7. Likert, Rensis, New Patterns of Management, McGraw-Hill Book Company, New York, New York, 1961.

8. Cooper, Joseph D., The Art of Decision Making, Doubleday, Garden City, New York, 1961.